FORECASTING METHODOLOGIES FOR USAF FACILITY MAINTENANCE AND REPAIR FUNDING REQUIREMENTS

THESIS

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Presented to the Faculty of the Graduate School of Engineering of the

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In Partial Fulfillment of the Requirements

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Gregory R. Ottoman

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Abstract

Eighteen methodologies for forecasting facility maintenance and repair funding requirements were investigated and analyzed to determine which methodology is best suited for use by the United States Air Force (USAF). The literature review identified four primary factors, or criteria, that determine facility maintenance and repair funding requirements. The methodologies were scored against the four criteria with respect to their appropriate application to USAF requirements. An analysis of dominance was accomplished; the results suggested that no one methodology was clearly superior. Fourteen of the methodologies were dominated, and consequently eliminated from further analysis. Four methodologies were non-dominated: the U.S. Army Construction Engineering Research Laboratories (USACERL) BUILDER; USACERL Maintenance Resource Prediction Model; U.S. Army Installation Status Report; and the USAF Plant Replacement Value-Facility Investment Metric (PRV-FIM). Further analysis was accomplished using the multi-criteria decision-making techniques of lexicographic analysis and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The results suggested the USAF PRV-FIM methodology is only preferable when the most important consideration is limiting the amount of data that must be collected and maintained. Otherwise, the USACERL BUILDER methodology may best serve the USAF in justifying to Congress and the public, its facility maintenance and repair level of investment determination.

FORECASTING METHODOLOGIES FOR USAF FACILITY MAINTENANCE AND REPAIR FUNDING REQUIREMENTS

I. Introduction

General Issue

With respect to maintenance and repair of public buildings, the Building Research Board (BRB), National Research Council (NRC) made the following statement in the introduction of its report *Committing to the Cost of Ownership: Maintenance and Repair of Public Buildings*:

> Public agency managers and elected officials, faced with the constant challenge of balancing competing public priorities and limited fiscal resources, often find it easy to neglect the maintenance and repair of public buildings . . . . The cumulative effects of wear on a facility are slow to become apparent and only infrequently disrupt a facility's users. Managers of facilities seldom have adequate information to predict when problems will occur if maintenance efforts are deferred. These managers are often poorly equipped to argue persuasively the need for steady commitment to maintenance. Underfunding of maintenance and repair is such a prevalent practice in the public sector that it has become in many agencies a *de facto* policy that each year compounds the problem as the backlog of deficiencies grows (BRB, 1991: 1-2).

The report then makes a very strong statement:

> Neglect of maintenance can . . . cause long-term financial losses as buildings wear out prematurely and must be replaced. Decisions to neglect maintenance, whether made intentionally or through ignorance, violate the public trust and constitute a mismanagement of public funds. In those cases where political expediency motivates the decision, it is not too harsh to term neglect of maintenance a form of embezzlement of public funds, a wasting of the nation's assets (BRB, 1991: 2).

While one may view this position as extreme, it is clear that facility maintenance is a significant responsibility of federal, state, and local governments. The scope of this task is enormous. It is estimated that the replacement value of federal, state, and educational facilities is approximately $2 trillion (APWA, 1990: 1). The Department of Defense (DoD) is responsible for maintaining a 1.4 billion square feet facility inventory, with an annual operations and maintenance budget of $4.4 billion (GAO/NSIAD, 1997: 4-6).

There are three components of a successful facility maintenance program: adequate funding for maintenance and repair, a good condition assessment program, and effective maintenance management (BRB, 1991: ix-x). While all three components are important, adequate funding is crucial; no maintenance program can be successful for long with out it.

Within the DoD, funding for facility maintenance is typically treated as a residual category after funding for weapon system modernization, personnel, training, and quality of life. In other words, the question asked in determining the facilities maintenance budgets is not how much is required, but rather how much is left over after everything else is paid for. The residual treatment of facility maintenance budgeting has proven to be inadequate in meeting the maintenance needs. The present funding situation is not encouraging; according to a GAO report:

> Over the past 10 years, the reduction in the number of DoD facilities worldwide, as measured by square footage of space, was only about 10 percent. . . . However, funding by the services for real property maintenance during the same time period decreased almost 40 percent. As a result, installations have growing backlogs of deferred maintenance and repair projects (GAO/NSIAD, 1997: 2).

If this situation continues long enough, it will eventually become a crisis.

As an alternative to treating maintenance as a residual funding category, one must have a process that determines the actual maintenance budget requirements. The process used, as well as the results, must be defensible to the decision-makers. This is essential in light of the ever-present competing priorities. While constrained budgets and competing priorities are a fact of life, government decision-makers and facility managers have a responsibility, as stewards of public facilities, to ensure public facilities receive adequate maintenance.

The United States Air Force (USAF) currently is making efforts "to improve the methodology used to determine the level of investment necessary to maintain their real property needs" (CERF, 1996: v). The maintenance funding guideline currently being followed is the result of the recommendations and findings of a 1989 DoD report to Congress titled *Renewing the Built Environment*. Based on sessions with operational advisors and historical funding trends in 1985-1987, the committee established a goal based on the plant replacement value (PRV). The goal was to budget 1% of PRV annually for service calls and recurring work and 0.75% of PRV annually for non-recurring work and minor construction.

Many other methodologies have been proposed, by other organizations and researchers, to determine the appropriate level of investment required to maintain facilities. These methodologies are typically in the form of models that predict maintenance funding requirements given inputs representing the physical plant in question. Methodologies based on PRV are prevalent; however, there are several other

approaches including formula budgeting methodologies (i.e. cost per square foot), condition assessment methodologies, and life-cycle methodologies.

The USAF has begun the process of improving the methodology used to determine the level of investment (LOI) necessary to maintain their real property needs. This was accomplished through a study prepared for the USAF by the Civil Engineering Research Foundation (CERF) titled *Level of Investment Study: Facilities and Infrastructure Maintenance and Repair*. The study compared the USAF LOI in facility maintenance with that of similar public sector agencies and private industry, and then attempted to determine "a composite real property industry standard suitable for use in the LOI determination process" (CERF, 1996: 4).

The conclusion reached was the USAF LOI is comparable to the LOI seen in the public and private sector, however it is probable the USAF is underspending on maintenance and repair along with the public and private sector. This approach asks what everyone else is spending, rather than what the appropriate LOI should be. It has not been effective when defending budget requests to USAF senior leadership and Congress.

Several alternative methodologies for determining the LOI were identified in the study but no standard or established methodology was identified, and no substantiated recommendation was reached as to what methodology is most appropriate.

In summary, it appears the USAF, along with the majority of the public and private sector, is underfunding maintenance and repair, and does not have an established methodology to determine what is the appropriate LOI. Several methodologies exist that attempt to determine the appropriate LOI, however no objective comparison has been

accomplished to determine which methodology is best suited for use in the USAF LOI determination.

Problem Statement

The USAF does not have an established methodology to determine funding requirements for maintaining facilities at a level without further degree of degradation. The existing practice of requesting funding at 1.75% of the PRV was established based on the recommendation of a DoD committee in the *Renewing the Built Environment* report. There is little documented evidence that active consideration was made to ascertain if it is the best, or even an adequate, methodology for determining preservation maintenance funding requirements. There are numerous methodologies which have been proposed in addition to the 1.75% of PRV model. There has not been an effort to determine which methodology is best suited for use by the USAF through establishing the salient criteria which determine facility maintenance requirements, and accomplishing an objective comparison based on these criteria.

Research Objectives

The objective of this thesis is to investigate the available methodologies for determining facility maintenance funding requirements, and determine which methodology is best suited for use by the USAF. The research is focused around the following research questions:

1. What categories or classes of methodologies have been developed to predict facility maintenance and repair funding requirements?

2. Is the existing USAF PRV-FIM methodology clearly superior in its appropriate application to USAF requirements? If not, are any of the methodologies identified through this research clearly superior?

3. If no one methodology is clearly superior, which methodologies are non-dominated, or in other words, are based on criteria that are the primary contributors to determining maintenance funding requirements?

4. Of the methodologies that are non-dominated, over what ranges of preferences among criteria are certain methodologies preferred over others?

Scope and Limitations

The research is confined to investigating existing methodologies. The research effort will not attempt to validate the output of the methodologies, but rather evaluate the process by which the methodologies predict maintenance funding requirements. This effort will focus specifically on USAF facility maintenance funding requirements. The research will not cover maintenance funding requirements for infrastructure, such as electrical distribution systems, roads, and airfield pavements.

II. Literature Review

Chapter Overview

Numerous federal and state government agencies, colleges and universities, public schools, and private organizations have examined the issue of facility maintenance and repair. As a result, several methodologies for predicting maintenance and repair requirements for facilities have been proposed. In order to establish a foundation for comparing methodologies, a single definition of the maintenance and repair budget is established in this chapter. The review of the literature suggests methodologies can be organized into four general classes or categories:

1. Plant Value Methodologies
2. Formula Methodologies
3. Life Cycle Methodologies
4. Condition Assessment Methodologies

The literature on facility maintenance identifies several criteria that are considered primary factors in determining facility M&R funding requirements. These criteria form the basis upon which the methodologies are compared against each other in this research effort. Finally, this chapter examines the selection of Multiple Criteria Decision Making (MCDM) methods.

The Maintenance and Repair Budget

The terms "maintenance and repair" often mean different things to different people. An objective comparison between the different methodologies for determining

funding requirements is difficult unless a single definition is established. The Federal Facilities Council (FFC), an activity of the Board of Infrastructure and the Constructed Environment of the National Research Council (NRC), recognized and addressed this problem in *Budgeting for Facilities Maintenance and Repair Activities* (FFC, 1996). The FFC is sponsored by most of the major federal facility owners, including the United States Air Force, Army, and Navy. Use of the FFC definition of M&R budgets is appropriate in light of the consensus of federal agencies, which sponsor the council in general, and the sponsorship by the USAF specifically.

Maintenance is defined as: "the upkeep of property and equipment, work necessary to realize the originally anticipated useful life of a fixed asset" (BRB, 1990: 3). Repair is defined as: "the restoration of a facility or component thereof to such a condition that it may be effectively utilized for its designated purposes . . . " (FFC, 1996: 8). Another way to look at the difference is that "repairs are curative while maintenance is preventive" (BRB, 1990: 3). While these definitions are commonly accepted, there is often disagreement as to what items are appropriately included in federal M&R budgets for facilities.

The FFC concluded that the following items are appropriately included in the M&R budgets for federal facilities:

1. Preventive maintenance: the planned, scheduled periodic inspection, adjustment, cleaning, lubrication, parts replacement, and minor repairs of equipment and systems.
2. Programmed major maintenance: tasks whose cycles exceed one year.
3. Predictive testing and inspection: activities that identify maintenance requirements.
4. Routine repairs: actions taken to restore a system to its original capacity, efficiency, or capability.
5. Service calls: unscheduled, unanticipated repairs.

6. Replacement of obsolete items: considered M&R work if required for the continued operation of facility, such as compliance with new codes or to replace an item for which spare parts are unavailable.

Similarly, the following items are not included in M&R budgets:

1. Operational activities: includes such things as custodial, snow removal, grounds care, security and fire control, pest control, and refuse collection.
2. Central utility and plant operations: includes electricity, heating, cooling, water, and sewage.
3. Alterations to facilities: includes expansion or changes to the function of a facility
4. Support for special events of activities

The FFC members agreed upon the above items; however, an important issue was not resolved: whether or not to include the backlog of M&R work in the M&R budget.

Given that a backlog of maintenance and repair (BMAR) is present, some methodologies include funding for BMAR reduction in the determination of the M&R budget; others establish BMAR reduction as a separate issue and do not include it. During the time this research effort was accomplished, the USAF was instituting a new facility M&R program called the Air Force Facility Investment Metric (FIM). This program is discussed in chapter four. Inherent to the FIM program is the recognition by the USAF that a significant amount of BMAR exists; however, budget restrictions will not permit a reduction of this backlog as an independent effort. BMAR requirements must compete on an equal basis with current requirements.

Methodology Categories

Numerous methodologies have been developed by researchers and agencies charged with facility management responsibilities. These methodologies tend to fall into four general categories: replacement value methodologies; formula methodologies; life

cycle methodologies; and condition assessment methodologies. No single source was found during the process of this research that proposed these exact categories. The first three categories are identified in the American Public Works Association (APWA) report, *Plan. Predict. Prevent. How to Reinvest in Public Buildings* (Melvin, 1992: 45-53). The use of condition assessment as a primary means of predicting M&R requirements is mentioned in several sources, including *Committing to the Cost of Ownership* (BRB, 1990) and *Maintenance Resource Prediction in the Facility Life-Cycle Process* (Neely et al., 1991). Many of the methodologies do not fall neatly into one category; they are hybrids of two or more categories. Nevertheless, these four categories serve as a useful framework to evaluate and analyze the different methodologies.

<u>Plant Value Methodologies.</u> Models within this category correlate annual M&R costs with the plant value. Plant value methodologies are based upon the central premise that, given an inventory of facilities, the value of the inventory can be used to predict M&R costs. The plant value "gives an indication of the size of the inventory and also the sophistication of the technology employed . . . " (DoD, 1989: 27). Methodologies in this category spring from the assumption that plant size and complexity are primary indicators of M&R requirements. Plant value is used in other methodologies, especially formula methodologies; however, for plant value methodologies, the plant value is the only factor directly used to determine M&R budget requirements (Melvin, 1992:45-46).

Proponents of this approach claim "Budgeting by facility value is one of the more reliable means of correlating facility needs to a budget . . . " (Barco, 1994: 30). Others claim "there is little reason to believe that building replacement value alone is an accurate predictor of maintenance costs." (Melvin, 1992: 46). The plant value methodologies are

suggested as being suitable as a policy recommendation for setting M&R budgets, rather than an absolute determination of the appropriate level of investment in M&R (Melvin, 1992:45). The bottom line is that, in the absence of other accepted methodologies, the plant value methodology is the recommended means of determining the required M&R budgets for federal agencies (FFC, 1996: 1).

Before moving to the next category, some discussion of how plant value is determined is warranted. There are two alternative methods to determine the plant value. The first method is based upon the original acquisition cost and defines current plant value (CPV) as the initial acquisition cost of a facility, adjusted to the current year by taking into consideration inflation, improvements, and changes in capacity (Barco, 1994: 29). The second method is based upon the use of unit cost factors, and defines plant replacement value (PRV) as the "cost to replace the facility with one of equivalent capacity and function" (Barco, 1994: 29). The unit cost factors ($/SF) are normally based upon the facility type.

The USAF is currently using both methods, and calls them both PRV regardless of the method used. The preferred method is to use the unit cost factor method; however, there are several facilities that do not have the facility type recorded in the real property records. In that case, the CRV method is used. The records for which no facility type data is available are being reviewed. Once all the records are updated , the unit cost factor method will be used for all facilities.

The DoD uses the term plant replacement value (PRV) (DoD, 1989: 4) and the Federal Facilities Council uses current replacement value (CRV) (FFC, 1996:10-11) to describe the plant value, regardless of which of the two methods described above are

used. In the process of analyzing models for this research, the two different methods of determining plant value will be analyzed individually. They will be referred to as CPV and PRV, as defined by Barco.

Formula Budgeting Methodologies. Methodologies within the formula budgeting category are based upon the idea that annual funding requirements can be determined through the application of formulas. The methods vary from simple, single variable formulas to complex, multiple-formula algorithms using multiple variables. Budget formulas are "sets of statements that detail a procedure for using predetermined fixed factors to manipulate variable data applicable to an institution in order to determine future funding requirements" (Monterecy, 1985: 17).

The variables used in budget formulas are generally readily quantifiable physical attributes that represent the facility inventory. Examples include size (i.e. square feet) and age. Variables are also used to represent facility attributes that are not as easily quantified. Examples include facility type (i.e. dormitory, warehouse, etc.), quality of construction, type of construction, and climate (Kaiser, 1995: 24). Once the variables are established, cost factors are applied to the variables to determine M&R budget requirements.

Life-Cycle Methodologies. Life-cycle methodologies are based on the concept that future M&R requirements for a facility can be predicted by breaking down a facility into its systems and components (i.e. electrical, HVAC, and roofing) and applying life-expectancy or life-cycle concepts to those systems and components (Melvin, 1992: 48). The use of facility system and component life-cycles results in estimations of the frequencies for repair or replacements. Once expected frequencies of repair and

replacements are established, cost data can be applied to generate expected funding requirements. Depending on the model, the cost data comes from a variety of sources. Common sources include the *R.S. Means Square Foot Costs* or *Dodge Construction Systems Costs* (Melvin, 1992: 52) and the U.S. Army Corp of Engineers (USACE) cost estimating manuals (Neely et al., 1991: 311).

The number of components or systems considered by a model varies. One recommendation is eight systems, including: foundations; roofing; exterior closure; interior walls; HVAC; plumbing; electrical; and fire and safety (Melvin, 1992: 49). The level of detail to which each system is modeled varies, depending on the particular methodology. At the low-end of detail, systems are very general. For example, a roofing system is not separated into gabled or built-up roofs, but simply considered a roof. An example of a much higher level of detail is the Maintenance Resource Prediction Model (MRPM), developed by the U.S. Army Construction Engineering Research Laboratory (USACERL). The MRPM provides for a level of detail that includes thousands of specific maintenance tasks on the different subsystems, such as removal and replacement of roof shingles (Neely et al., 1991: 11).

Condition Assessment Methodologies. This category attempts to determine facility M&R requirements based on condition assessment of the facility inventory. There tend to be two different approaches within this category. The first is to determine the appropriate maintenance and repair budget based upon "completing condition assessments followed by cost estimates to perform maintenance and repair for deficiencies noted" (CERF, 1996: 18). The second approach uses condition assessments as a basis upon which to predict the remaining useful life of a facility component, and

consequently, the future maintenance and repair requirements. The first method focuses on immediate and deferred maintenance needs, while the second method provides for long-term planning and prediction (Melvin, 1990: 22).

Primary Factors in Determining Facility M&R Budget Requirements

Many research efforts and committee reports have dealt with various issues of facility maintenance and repair. Several of these propose a number of primary factors, or characteristics, which have a major influence on the appropriate level of funding for M&R of facilities. With regard to these characteristics, the NRC stated:

> While the M&R component of the cost of ownership will vary from building to building, it is possible to develop a consistent relationship between this component and characteristics of an inventory of buildings. A variety of such relationships are in use to estimate average levels of the cost of M&R (BRB, 1990: 9).

This section examines several research efforts and reports and determines which characteristics and factors the authors consider to have a major influence on the appropriate level of funding for M&R of facilities.

Monterecy, 1985. A dissertation by Monterecy applied a formula budgeting model to the forty Rhode Island school districts and concluded that it was a "reasonable tool for estimating physical plant maintenance needs" (Monterecy, 1985: 104). Monterecy found there was moderate partial correlation between the variables representing age of plant, current replacement value, and size (square feet) of the Rhode Island schools, and the maintenance requirements, as measured by the Dergis-Sherman budgeting formula (Monterecy, 1985: 85). Monterecy also pointed out that the educational budget process, like any tax revenue funded process, is a political process. Unlike many other

requirements, the physical plant usually does not have a strong advocate or constituency. If the funding process does not illustrate the acceleration of maintenance requirements, and increased costs in the future as a result of inadequate M&R, then underfunding of the facility M&R component is likely (Monterecy, 1985: 109).

Phillips, 1989. Phillips reported on a variation of the Dergis-Sherman formula that was used by the Alabama Commission on Higher Education to prepare estimates of the facility M&R requirements for Alabama's college and university facilities. Phillips proposed that use of age and replacement costs allow for a reasonable estimate of funding requirements for M&R. The replacement cost Phillips considered was that of each component system of a building, considered separately. The replacement cost is adjusted according to facility size, facility type, type of construction, and location (Phillips, 1989: 31). Phillips also allowed for the age of a facility to be adjusted, by means of a formula, to reflect the effect of renovations. The methodology proposed by Phillips was based on the idea that facilities consist of different major systems, which all have different life expectancies and M&R costs associated with them. This results in M&R costs that are not constant over time.

Hutson and Biedenweg, 1989. Hutson and Biedenweg developed a model for M&R requirements at Stanford. They describe age, replacement cost of individual facility systems, and facility type as "features that would have an impact on facility and system wear-out and the resulting replacement and renewal costs" (Hutson and Biedenweg, 1989: 14-15). Size is a critical factor because replacement cost is calculated as cost per square foot. The life-cycle of facility subsystems is identified as being a critical factor. "These cycles are critical in determining the necessary, and varying,

funding levels for future years" (Hutson and Biedenweg, 1989: 13). The life-cycles of facilities and their individual systems, result in funding requirements which are not constant over time.

Barco, 1994. A journal article by Barco presented a list of key facility attributes. The list includes location, facility type, year acquired (age), acquisition cost, size, capital improvements, current value, and replacement value (Barco, 1994: 28). Barco states that as these variables "trend up or down, so does the justification for maintenance and repair resources for the affected facilities." (Barco, 1994: 29) Facility condition is also an important consideration when determining M&R budget requirements (Barco, 1994: 30).

Kaiser, 1995. In an article titled *Preventing Deferred Maintenance*, Kaiser lists several factors that must be considered in planning and budgeting for facility maintenance and repair. Funding requirements will "vary by region, climate, building type, type and quality of original construction, the extent of use and abuse and maintenance management." (Kaiser, 1995: 24) Kaiser also states the following factors should be considered in any model: size, age, previous renewals and renovations, and previous levels of maintenance funding. A good maintenance funding model should "be multivariate that weighs characteristics of a facility" (Kaiser, 1995:28). Kaiser also indicates that inadequate M&R budgets will have an effect on future requirements (Kaiser, 1995: 24).

Building Research Board, 1990. The Federal Construction Council (FCC) is an organization consisting of members from many federal agencies, including the all DoD agencies. The FFC requested the Building Research Board (BRB) of the National Research Council (NRC) to "undertake a broad review of the operation, maintenance and

repair activities of federal facilities" (BRB, 1990: 2). This concern was echoed by the BRB's Public Facilities Council (PFC), which includes representatives from state and local government agencies. The result was a joint research effort by the BRB Committee on Advanced Maintenance Concepts for Buildings and the American Public Works Association (APWA). The findings and recommendations were published in a report titled *Committing to the Cost of Ownership: Maintenance and Repair of Public buildings* (BRB, 1990). The findings and recommendations of this report were a result of research by over fifty professionals and experts in M&R of public facilities.

The primary recommendation of *Committing to the Cost of Ownership* is an appropriate level of M&R funding should be between 2 and 4 percent of the current replacement value of the facility inventory (BRB, 1990: 10). Several factors were listed which need to be considered while determining the funding level within the wide range of 2 to 4 percent. These factors include building size, types of finishes, current age and condition, type of occupants or users, climatic severity, tenancy turnover rates, and location as represented by labor and material costs (BRB, 1990: 9).

An effective budget model should incorporate the long-term consequences of neglecting maintenance and repair. *Committing to the Cost of Ownership* emphasized that a long-term viewpoint is important: "It is often difficult to discern the direct consequences of neglect of M&R because physical evidence may not be immediately visible" (BRB, 1990: 6). The report asserts that trade-offs result when the maintenance budget is not funded adequately. Inadequate M&R funding can result is increased operating costs, social costs, and "the crisis management condition" (BRB, 1990: 6). In a

crisis management condition, "Hasty decisions are often made, with expensive and even inappropriate products and services purchased" (BRB, 1990: 6).

Another important aspect of predicting facility maintenance and repair requirements is the effective use of condition assessments coupled with the concepts of facility system and component life-cycles. The report states:

> Predictions or estimates of the remaining useful life of a component must often be made . . . . Effective condition assessments depend on such predictions, which then become the basis for establishing the repair components of the M&R budgets (BRB, 1990: 14).

This concept was identified for further study, as a second phase to the *Committing to the Cost of Ownership* research.

Melvin, 1992. The report titled *Plan. Predict. Prevent. How to Reinvest in Public Buildings* was written by Melvin with the assistance and input from 43 project sponsors. Sponsors of the report included the Canadian Armed Forces, numerous state and city governments, and the University of North Carolina, Chapel Hill.

Building on the findings and recommendations of *Committing to the Cost of Ownership*, Melvin stressed the "need to shift from a crisis management approach to one emphasizing reinvestment and planning" (Melvin, 1992: v). His finding that:

> Instead of protecting building assets from deterioration, most agencies are now provided only with the means to respond to emergencies – to correct only those conditions which immediately threaten facility operations . . . decsionmakers need to be convinced that giving up these short-term practices in favor of planned maintenance and reinvestment will yield long-term benefits (Melvin. 1992: v).

highlights the need for an effective budget model to consider the effect on future M&R funding requirements of not funding M&R at an adequate level over the short-term.

Melvin reiterates the findings of *Committing to the Cost of Ownership* on the issue of characteristics of facilities that should be considered when determining appropriate funding levels for M&R. They are age, replacement cost, facility type, size, climate, type of construction, previous level of maintenance, location and intensity of use (Melvin, 1992: 45-52).

Melvin does balance the need for considering a multitude of characteristics against the cost involved with gathering and supporting the required data. With respect to the various methodologies for determining budget requirements, "the choice of method depends on the several factors, including cost, need for accuracy, ease of application, staff resources, and data management capabilities" (Melvin, 1992:45).

The concept of life-cycle analysis is one of the central concepts of this report. When planning and budgeting for building maintenance, Melvin asserts that "the mechanism is grounded on what is called life-cycle analysis of component replacement requirements and costs" (Melvin, 1992: 44). Condition assessments are also considered important in order to have a "fully developed and integrated" model. An integrated model would combine condition assessment data with theoretical life-cycle standards to improve the model's accuracy and power to predict requirements over a long time span (Melvin, 1992: 49).

<u>Neely et al., 1991</u>. The U.S. Army Corps of Engineers (USACE) directed the U.S. Army Construction Engineering Research Laboratory (USACERL) to develop a M&R cost database containing M&R cost data for Army facilities, and prediction models for future maintenance requirements of the Army facility inventory (Neely et al., 1991: 5). The resulting model was called the Maintenance Resource Prediction Model (MRPM).

In a report on this research effort, it was suggested that methods using formulas based upon simple ratios to project future funding requirements are not accurate given the "variety in age of facilities, missions supported, construction methods, climate, and other factors." (Neely et al., 1991: 37) The use of life-cycles was central to this research effort, and Neely et al. stated "Because of the identifiable life cycle of both facilities and their installed subsystems . . . These cycles are critical in determining the necessary, and varying, funding levels for future years" (Neely et al., 1991: 37). Condition assessments were claimed to have limited use in predicting long term M&R requirements, although they do provide accurate determination of current condition and short-term needs (Neely et al., 1991: 37).

Civil Engineering Research Foundation, 1996. In a effort to improve the methodology used to determine the LOI necessary to maintain the real property assets of the USAF, a study titled *Level of Investment Study: Facilities and Infrastructure Maintenance and Repair*, was accomplished by the Civil Engineering Research Foundation (CERF). One of the primary tasks of this study was a general review of the body of literature pertaining to facility M&R issues. The other task was to develop and analyze the results of a survey. The survey was self-administered and returned by 29 institutions such as universities, airports, private companies, and utilities. The fundamental purpose of the survey was to determine the funding levels for M&R and PRV by each facility and infrastructure category for a variety of institutions. The results were compared to the AF level of investment.

The survey results indicated that the "Air Force LOI in facilities maintenance and repair is comparable to the LOI seen in public and private organizations." However,

"none of the organizations (surveyed) reported whether or not their LOI was adequate or appropriate for maintaining their infrastructure" (CERF, 1996: 40). This approach determined that the AF is funding at about the same level as 29 other institutions, but did not reach any conclusion concerning if the levels of investment were adequate.

One of the findings of this report were that "the appropriate LOI for facilities and infrastructure will depend on several factors, including facility type, age, size, use, complexity, and geographic region" (CERF, 1996: 39). Concerning the need to use a model that predicts the effect one future M&R funding requirement of not funding M&R at an adequate level, the study concluded that:

> The link between underfunding of maintenance and the possible negative consequences of doing so is seldom made when preparing for maintenance and repair budgets, yet this link is crucial in justifying the LOI needed for maintenance and repair (CERF, 1996: 39).

The study echoed the findings of other researchers concerning a common reason for underfunding M&R requirements. It is because the results of an adequate M&R program are not readily visible to facility users and funding decision-makers, and the consequences of underfunding do not appear over the short-term. This results in a low profile for M&R in contrast with other pressing funding requirements. (CERF, 1996: 9-10)

Hjelmstad et al., 1996. Researchers at the U.S. Army Construction Engineering Research Laboratory (USACERL) developed a prototype Building Materials Durability Model (BMDM) which uses algorithms representing building materials durability parameters and environmental stimuli. The model is still in development stages at this time and is primarily focused on determining life-cycle costs of decisions of initial

material selection of new construction. It does indicate that climate and type of construction have an impact on the long-term maintenance costs (Hjelmstad et al., 1996: 7). The use of life-cycles of materials is also inherent in this approach to determining long-term maintenance requirements. One of the goals of the BMDM model is to "assess the consequences of different repair strategies" (Hjelmstad, 1996: 65) which recognize that inadequate M&R can lead to increased costs over the life-cycle of a material.

Summary. Based on the review of the literature concerning budgeting for facility M&R, there appears to be an agreement between experts as to the primary factors that drive facility M&R requirements. These factors are summarized in Table 1.

Table 1. Summary of Primary Factors in Determining Facility M&R Requirements

Author	Age	Replacement Value	Size	Facility Type	Location	Climate	Type of Construction	Facility Condition	Life-Cycle	Penalty Cost
Monterecy, 1985	45	45	44							
CERF, 1996	39		39	39	23	23				10
Barco, 1994	28	28	28	28	28			30		
Phillips, 1989	34	31	31	31	31		31		31	
Hutson, 1989	15	15	18	14			13		14	
Hjelmstad, 1996	10				10	10	10	10	10	65
Neely, 1991	39	38	38	37	18	37	37	37	37	
Kaiser, 1995	27	27	27	27	27	27	27	28	29	24
BRB, 1990	9	10	9	9	9	9	9	9	22	6
Melvin, 1992	45	45	52	52	48	45	45	48	44	v
	Page Reference in Author's Source									

Multiple Criteria Decision Making

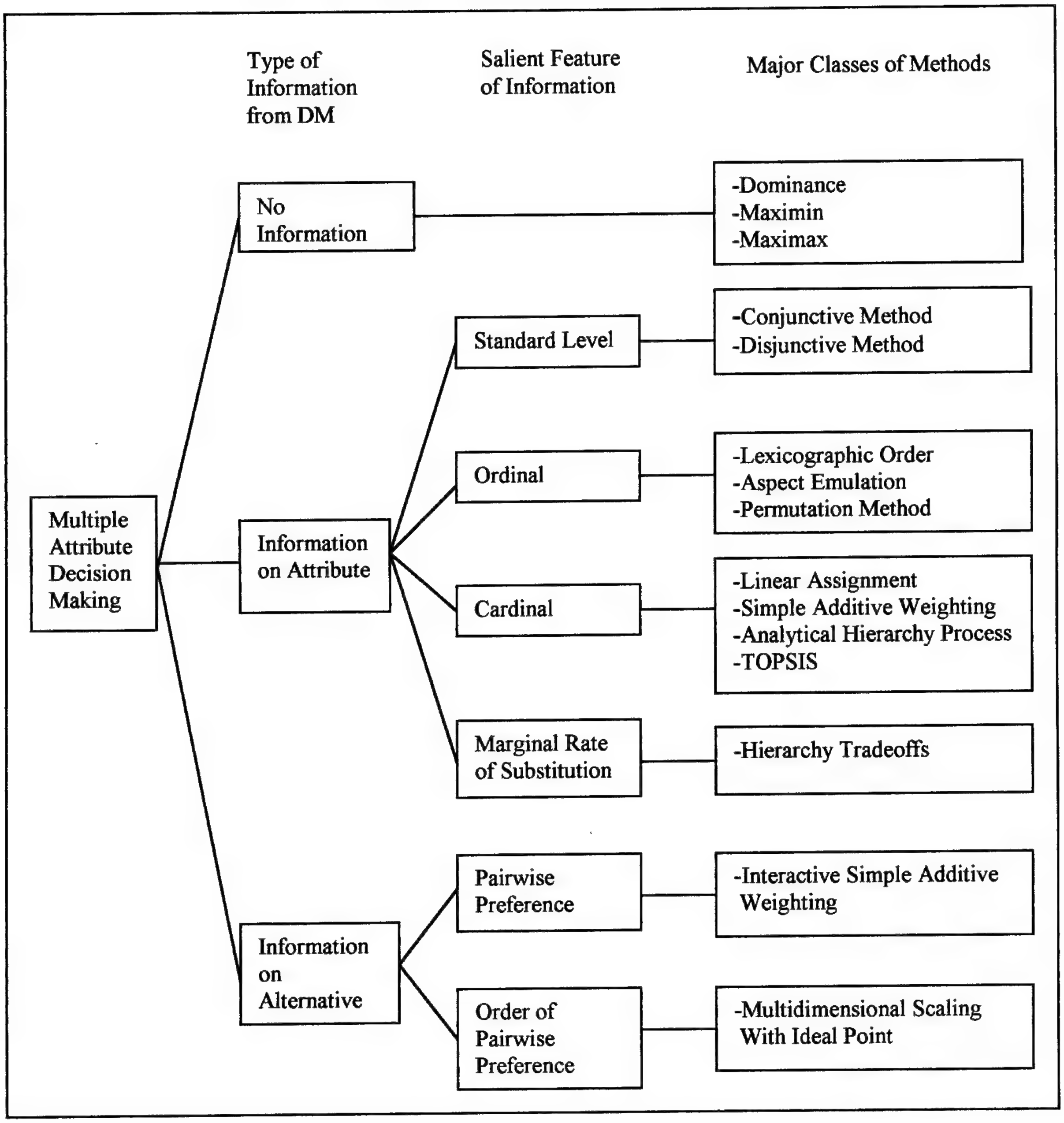
Decision Analysis is the process that "provides structure and guidance for thinking systematically about hard decisions" (Clemen, 1996: 2). The major steps of this process include identifying the decision and determining the objectives; identifying alternatives; modeling the decision; and choosing the preferred alternative. Multiple Criteria Decision Making (MCDM) refers to the area of decision analysis that deals with multiple criteria.

Decisions that are complex enough to require a systematic analysis commonly consist of multiple criteria or attributes. Consider a person trying to decide which new car model to purchase. Her decision could be based upon buying the car with the highest fuel economy, as measured by miles per gallon. This would be a relatively simple decision. More likely, she would consider several other criteria including style, safety, and price. Multiple Attribute Decision Making (MADM) is "a procedure that specifies how attribute information is to be processed in order to arrive at a choice" (Hwang and Yoon, 1981: 24).

There have been numerous MADM methods proposed. The MADM method that is applicable to a decision problem depends upon the type of information available from the decision-maker (DM), and the salient feature of the information (Hwang and Yoon, 1981: 8). The taxonomy of MADM methods presented by Hwang and Yoon (see Figure 2) illustrates this concept.

The first issue is determining the type of information that is available from the DM. If there is no information from the DM, there is no need to determine the salient features of information. If there is information on the attributes, it can be standard level, ordinal, cardinal, or marginal rate of substitution.

Figure 1. A Taxonomy of Methods for MADM (From Hwang and Yoon, 1981: 9)



Standard level information on the attributes means the DM sets minimal levels for attribute values; an alternative that does not meet those levels is rejected. Ordinal information is the relative importance among the attributes. Cardinal preference refers to representing the DM's preference between attributes as a set of quantitative weights. Information concerning the marginal rates of substitution refers to being able to define the tradeoffs between attributes. If a lower value is accepted for one attribute, then what increased value in the other attributes is required to make the DM indifferent between the tradeoff?

Information on alternatives may be solicited from the DM. The two features of this information are pairwise preference and order of pairwise preference. Information on pairwise preference requires the DM to indicate preference between two alternatives. Order of pairwise preference requires "ordering of the proximities of pairs of alternatives . . . to construct a multidimensional spatial representation" (Hwang and Yoon, 1981: 176).

The information available from the DM is a critical factor in the selection of an appropriate MADM method, however, there are other considerations. The DM must have trust and confidence in the method. "Some MCDM methods are justified by their axiomatic base, whereas other methods are substantiated by their intuitive appeal and ease of use" (Ozernoy, 1992: 162). In order for the DM to benefit from the analysis, the theory behind the methods should be understood and accepted by the DM.

Conclusion

This chapter established a single definition for the maintenance and repair budget. This definition provides a foundation for evaluating the different methodologies. The review of the literature suggests that different processes for determining M&R funding requirements can be classified according to four methodology categories.

This chapter established several criteria that are considered primary factors in determining facility M&R funding requirements. These criteria form the basis upon which the methodologies are compared against each other in this research effort. Finally, this chapter briefly examined issues in the selection of Multiple Criteria Decision Making (MCDM) methods.

III. Methodology

Chapter Overview

The purpose of this chapter is to outline the methodology used to resolve the research questions. The first step was to define a scale for each of the four criteria established in the review of the literature. The scales were used to quantitatively score the methodologies against the criteria. The second step was to identify existing methodologies and score the methodologies. In addition to scoring against the four criteria, the methodologies were categorized according to the four general approaches described in Chapter Two.

The process of identifying methodologies was accomplished through a review of the literature, and contacting organizations that are responsible for maintenance and repair of facility inventories comparable with that of the USAF. This research effort identified and evaluated eighteen methodologies.

The third step was to determine if any one methodology is clearly superior. This was accomplished through a dominance analysis of the criteria scores for each methodology. Where no one methodology is clearly superior (dominant), then the non-dominated methodologies were considered further, while the dominated, or inferior, methodologies were discarded from further analysis.

The fourth step was to use the multi-criteria decision making (MCDM) tool known as lexicographic ordering. This process provides a preference ranking of the non-dominated methodologies, based upon the order of importance of the criteria. The fifth

step was to use the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method. TOPSIS provides a preference ranking of the methodologies based on the concept that the preferred methodology is closest to as ideal methodology, and farthest from a negative-ideal methodology.

Establishing the Criteria and Criteria Scales

The review of the literature resulted in the identification of several factors, considered by the Building Research Board and other experts, to have a major influence on the appropriate level of funding for M&R of facilities. Given that a methodology for determining facility M&R requirements should consider these factors to the greatest extent possible, the factors are appropriate for use as criteria in the evaluation of the facility M&R budgeting methodologies. The factors summarized in Table 2 are of three distinct types: Salient Characteristics; Life-Cycle; and Penalty Cost.

Table 2. Revised Summary of Primary Factors

	Criterion 1								Criterion 2	Criterion 3
	Age	Replacement Value	Size	Facility Type	Location	Climate	Type of Construction	Facility Condition	Life-Cycle	Penalty Cost
Monterecy, 1985	45	45	44							
CERF, 1996	39		39	39	23	23				10
Barco, 1994	28	28	28	28	28			30		
Phillips, 1989	34	31	31	31	31		31		31	
Hutson, 1989	15	15	18	14			13		14	
Hjelmstad, 1996	10				10	10	10	10	10	65
Neely, 1991	39	38	38	37	18	37	37	37	37	
Kaiser, 1995	27	27	27	27	27	27	27	28	29	24
BRB, 1990	9	10	9	9	9	9	9	9	22	6
Melvin, 1992	45	45	52	52	48	45	45	48	44	v
	Page Reference in Author's Source									

Criterion 1: Salient Characteristics. The first criterion is a methodology that attempts to determine appropriate facility M&R funding requirements should consider those salient characteristics that impact facility M&R requirements. The review of the literature identified the eight characteristics shown in Table 2. They have been identified by experts to be the salient characteristics, factors that represent the physical state of the facility inventory.

These salient characteristics are considered by the different methodologies in a variety of ways. The purpose of this research is not to validate the methodologies and the manner in which they determine M&R requirements. Therefore, scoring of the methodologies against these characteristics will only consider whether the methodology considers, does not consider, or indirectly considers or calculates the characteristic.

An example of indirect consideration of a characteristic is the use of plant replacement value. When a methodology considers plant replacement value, it is indirectly considering size and facility type, because they were used to calculate the plant replacement value.

The methodologies shall be evaluated to determine whether the salient characteristics are considered as inputs to the methodologies. The methodologies will be evaluated and scored using a three-point ordinal scale, from one to three, for each of the eight characteristics. Note that a score of two is not necessarily twice as good as a score of one. A Score of two can simply be said to be better than one. This assumption holds true for the other criteria scoring as well. The score assigned will be based on the following basis:

Score of 1 Methodology does not consider the characteristic

Score of 2 Methodology indirectly considers the characteristic

Score of 3 Methodology directly considers the characteristic

Because the eight characteristics are combined in a single criterion, the issue arises as to how the scores for the individual characteristics are combined into an overall score for the criterion. During the literature review, all eight characteristics were cited as being salient characteristics; however; there is no consensus of expert opinion, nor any research that provides guidance on several important issues.

One issue is which characteristics are the most important, or how important they are in comparison to the others. Another issue is that consideration of one subset of the eight salient characteristics may result in more accurate modeling of the facility inventory than consideration of another, different subset. In other words, the combination of characteristics that are considered may have an impact. Unfortunately, only anecdotal evidence exists and there is a lack of peer-reviewed literature to support any position on these issues. Therefore, for purposes of this research, no characteristic shall be considered more important than any other characteristic. The score for the salient characteristics criterion will be the sum of the scores of the eight characteristics.

Criterion 2: Life-Cycle. This criterion considers that a methodology that attempts to determine appropriate facility M&R funding requirements should consider the life-cycles of facilities and their systems. A facility is comprised of several systems and subsystems, and that these systems have varying life expectancies. Maintenance and repair requirements are not constant over the life of a facility. A methodology that

considers these life-cycles will reasonably be expected to more accurately determine a facilities M&R requirements over time.

In the evaluation of methodologies against the life-cycle criterion, methodologies shall be evaluated according to the extent that the methodology represents the varying funding requirements of facilities over their life-cycles. The methodologies will be evaluated and scored using a five-point scale, from one to five. The score assigned will be based on the following basis:

Score of 1	Methodology does not consider life-cycles of facilities or facility systems
Score of 2	Methodology considers life-cycles of facilities in an indirect, or abstract manner
Score of 3	Methodology directly considers life-cycles of facilities as a whole, but does not break down the facility into major components or systems
Score of 4	Methodology directly considers life-cycles of the facilities major components and systems
Score of 5	Methodology considers life-cycles of the facilities major and minor components and systems

<u>Criterion 3: Maintenance Deferral Penalty Cost.</u> This criterion considers that methodologies should take into account the effect on future M&R funding requirements of not funding M&R at an adequate level. This criteria is based on the concept that neglecting preventive maintenance actions cause facility system and components to require repair or replacement earlier than if it received regular and timely preventative maintenance.

This criteria represents the predictive capacity of the methodology to provide outputs which illustrate the trade-off commonly referred to as pay now, or pay later. One

choice is funding at an adequate level, which is defined as the level that minimizes overall M&R costs over the lifetime of a facility. The other choice is funding at an inadequate level over the short-term, and facing increased funding requirements over the long-term, due to increased deterioration and failure rates of facilities and the associated systems and subsystems.

Methodologies shall be evaluated according to the extent that the methodology incorporates the maintenance deferral penalty costs, the effect on future funding requirements of not funding M&R at an adequate level. The methodologies will be evaluated and scored using a three-point scale, from one to three. The score assigned will be based on the following basis:

Score of 1	Methodology does not consider the effect on future funding requirements of not funding M&R at an adequate level.
Score of 2	Methodology indirectly or abstractly considers the effect on future funding requirements of not funding M&R at an adequate level.
Score of 3	Methodology directly considers the effect on future funding requirements of not funding M&R at an adequate level.

Criterion 4: Data Requirement. When evaluating almost any model, a central issue is how closely a methodology needs to reflect the real system being modeled. The more closely that a methodology represent the real system, the higher the data requirements. This issue is highlighted in a letter to the U.S. General Accounting Office from Mr. John B. Goodman, Deputy Undersecretary of Defense (Industrial Affairs and Installations) concerning a GAO report finding that the DoD does not currently have complete, reliable information on DoD infrastructure. Mr. Goodman responded:

> As with most organizations, DoD operates and makes decisions in the face of uncertainty, without "complete" information but with the best possible information. Data collection in an enterprise as large as DoD is potentially very expensive. With current resource constraints, each proposal to collect detailed data at the headquarters level must be carefully evaluated for its cost-effectiveness (GAO/NSIAD, 1997: 39).

Clearly, any methodology that is considered for implementation must take into consideration the data requirements inherent to the methodology. The USAF currently maintains facility and infrastructure data, such as real property inventory records. The ideal case would be a methodology that requires data that is available, maintained, and in an immediately useable format.

The methodologies shall be evaluated according to the extent that the methodology uses input data that is currently available to the USAF. The methodologies will be evaluated and scored using a six-point scale, from one to six. The score assigned will be based on the following basis:

Score of 1	Required input data is not available and not readily collectable
Score of 2	Required input data is not available, but could be collected and maintained with an extensive effort and expense.
Score of 3	Required input data is not available, but could be collected with an extensive effort, however maintenance of the date requires only low or moderate effort and expense
Score of 4	Required input data is not available, but could be collected and maintained with minimal effort and expense.
Score of 5	Required input data is available and maintained, but not in an immediately useable format for the methodology
Score of 6	Required input data is available and maintained, and is in an immediately useable format for the methodology

Investigation of Methodologies and Models.

The majority of the effort involved in this research was investigating and evaluating methodologies that determine the appropriate funding levels for M&R of facilities. The process of investigating the available methodologies consisted of literature review and personal interviews. The focus of this research was on methodologies applicable for use by the USAF. Therefore, investigation of the existing U.S. Air Force, U.S. Navy, and U.S. Army methodologies was a priority. Between the three major DoD services, they control almost 80 percent of the total federal property, plant and equipment inventory (GAO/AIMD, 1997: 4).

The methodologies were scored against the criteria using personal judgment of the researcher. It could be argued that it would be preferable to use a panel of experts to score the methodologies. A panel of experts was not used because the effort to investigate and understand the theory behind these methodologies required a considerable investment in time. In the case of the BUILDER methodology, for example, the evaluation process involved reviewing numerous articles, telephone interviews, and a site visit to the USACERL where the model is being developed. Identifying a group of experts who are already familiar with all the methodologies, or educating a group of experts on the entire spectrum of methodologies would have been a daunting task, even if such a group were willing to commit the time and energy required of them. It was decided that such an approach would require more effort than is reasonable in light of the potential benefit it would contribute to this research.

Analysis of Methodologies and Models

Once the methodologies were investigated and scored against the four criteria, they were analyzed. The purpose of the analysis was to answer research questions two through four. The analysis of the methodologies consisted of the application of three MCDM techniques: analysis of dominance, lexicographical ordering, and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

Analysis of Dominance. Research questions two and three concerned the determination of whether any of the methodologies are superior to the others, and if not, then which are not dominated by other methodologies. The set of non-dominated solutions is considered further, while dominated methodologies are eliminated from further analysis. Dominance does not require any preference information from a decision-maker and provides an objective solution.

A methodology is dominant if its score for at least one criterion is greater than the scores for that criterion of all the other methodologies, and its scores for the other criteria are equal to or greater than the scores for the other methodologies. A methodology is referred to as "non-dominated" if no other methodology dominates it.

Lexicographic Ordering. Lexicographic ordering is a MCDM technique that is appropriate when a decision-maker can specify which attributes, or criteria are most important, but can not specify cardinal weights between criteria. This technique was selected because of its simplicity and ability to rapidly consider a variety of criterion

preference orders. Lexicographic ordering easily accomplished using an Excel spreadsheet and the Excel sort function.

The process of lexicographic sorting begins with the decision-maker indicating which criterion is most important. The methodologies are ranked according to their scores for the most important criterion. If there are no tied scores for that criterion, then the lexicographic ordering is complete, and the methodologies are ranked in preference order according to their scores in the most important criterion. In the case where there are tied scores, then the decision-maker must specify the next-most important criterion, and the methodologies are compared on the scores of the next-most important criterion. This process repeats itself until there are no tied scores, or the criteria are exhausted.

This research effort does not include the preference of an actual decision-maker; however, with four criteria an exhaustive analysis of all the possible combinations of preference order among the four criteria is accomplished. This resulted in a decision tree that allows a decision-maker to select his or her preferences and follow the decision path to the appropriate lexicographical preference order among the non-dominated methodologies.

TOPSIS. The Technique for Order Preference by Similarity to Ideal Solution is a compromising model that selects an alternative that has the largest relative closeness to the ideal solution. The relative closeness to the ideal solution is accomplished by simultaneously evaluating the alternative's distance from the ideal solution and the negative solution. This techniques was selected because of its ability to consider criteria with different scales. The concept that a preferable alternative should be as close to the

best possible solution, and as far from the worst possible solution as possible, should be a reasonable concept for most decision-makers to accept.

The process of TOPSIS is relatively straightforward; however the technical discussion of the technique below may be difficult to follow for a reader that is unfamiliar with MCDM techniques. Therefore, the TOPSIS analysis in Chapter 4 includes an explicit example of the calculations.

Hwang and Yoon explain that the TOPSIS algorithm consists of six steps (Hwang and Yoon, 1981: 128-134).

Step 1. Construct the normalized decision matrix. This process transforms the attribute dimensions into non-dimensional attributes. In the case of this research, the attributes are the criteria scores. Because the scales for the criterion are not equal, they must be normalized to allow them to be compared using TOPSIS. This is done by dividing each outcome criterion x_{ij} (the score of the i-th methodology with respect to the j-th criterion) by the norm of the total outcome vector. The element r_{ij} of the normalized decision matrix R is calculated as:

$$r_{ij} = x_{ij}/(\Sigma x^2_{ij})^2$$

Step 2. Construct the weighted, normalized decision matrix. The set of weights for the criteria, $w = (w_1,w_2,w_3,....,w_j)$, where $\Sigma w_i = 1$ from the decision-maker are multiplied with each column of the R matrix to generate the weighted, normalized decision matrix V.

Step 3. Determine the ideal and negative-ideal solution. The ideal solution, I^*, is composed of all the best criterion scores from the methodologies being analyzed. The

negative-ideal solution, I^{-}, is composed of all the worst criterion scores from the methodologies being analyzed.

Step 4. Calculate the separation measure. The separation measure is the n-dimensional Euclidean distance between a methodology and the ideal and negative solutions. The separation measures are calculated for each methodology. The distance of a methodology form the ideal solution is:

$$S_{i*} = [\Sigma_j(v_{ij}-v_{j*})^p]^{1/p}$$

and the distance from the negative-ideal solution is:

$$S_{i-} = [\Sigma_j(v_{ij}-v_{j-})^p]^{1/p}$$

where V_{j*} and V_{j-} are the ideal and negative-ideal solution vectors and p is given a value of 1, 2, or ∞, according to the MCDM technique of L_p metrics. If p=1, then the separation is measured according to a Manhattan or rectilinear metric, otherwise referred to as a totally compensatory. If p=2, then the separation is measured according to Euclidean distance. If p=∞, then S_{i*} is the minimum deviation among the j criteria; the deviations for the remaining criteria are not considered. Likewise, S_{i-} is the maximum deviation among the j criteria; the deviations for the remaining criteria are not considered. The p=∞ case is referred to as totally non-compensatory, because the separation measure is defined solely by the most prominent criterion, while the remaining criteria are overwhelmed. Use of the Lp metrics, from p=1 to p=∞, permit the analysis to incorporate a range of decision-maker preference structures, from totally compensatory to totally non-compensatory.

Step 5. Calculate the relative closeness to the ideal solution. The relative closeness of a methodology with respect to I^* is defined as

$$C_{i*} = s_{i-}/(s_{i*} + s_{i-}) \text{ , where } 0 \leq C_{i*} \leq 1$$

The closer a methodology is to the ideal solution, the closer C_{i*} will be to a value of one.

Step 6. Rank the preference order. The methodologies are ranked in descending order of C_{i*}.

Conclusion

This chapter outlined the methodology used to resolve the research questions in Chapter four. The four criteria were established based on the review of the literature. Scales were constructed for each criterion. The process of identifying and scoring methodologies was explained. The analysis of the methodologies was accomplished using the MCDM techniques of dominance, lexicographic ordering, and TOPSIS.

IV. Research Results

Chapter Overview

This chapter presents the results of the research and analysis accomplished towards the resolution of the four research questions posed in chapter 1. These question were:

1. What categories or classes of methodologies have been developed to predict facility maintenance and repair funding requirements?

2. Is the existing USAF PRV-FIM methodology clearly superior in its appropriate application to USAF requirements? If not, are any of the methodologies identified through this research clearly superior?

3. If no single methodology is clearly superior, which methodologies are non-dominated in their appropriate application to USAF requirements?

4. Of the methodologies that are non-dominated, over what ranges of preferences between criteria, are certain methodologies preferred over others?

The format of this chapter follows the sequence of research questions listed above.

Investigation of Methodologies and Models

A large part of the research effort was the process of investigating available methodologies and models that determine appropriate facility M&R funding requirements. The models were gathered through a combination of literature search and interviews with personnel who developed and/or utilize the models. The models were evaluated against using the methodology established in chapter 3. This section includes descriptions and the scores assigned to each of the methodologies and models.

Percentage of Current Plant Value. This model is one of two strictly plant value-based models, the other being the percentage of plant replacement value model. The percentage of current plant value (CPV) model is very simple and is commonly cited in

numerous sources. The CPV model determines facility M&R budget requirements as a percentage of the current value of the facility inventory.

Annual Facility M&R Budget = X% x CPV of facility inventory

The CPV of a facility inventory is the original acquisition cost of each facility adjusted to the current or budget year, taking into consideration inflation, expansions, demolitions, and improvements (FFC, 1996: 10-11).

The percentage multiplier depends upon which source, or model is used. The DoD recommended 1% of replacement value annually for service calls and recurring work, and 0.75% of replacement value annually for non-recurring work and minor construction (DoD, 1989: 31). The Building Research Board of the National Research Council recommends a range of two to four percent (BRB, 1990: 10). This model is suitable for application to a large number of facilities as a whole, not to accurately predict M&R requirements for individual facilities (Melvin, 1992: 45).

Evaluation of Percentage of Current Plant Value Model.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The only characteristic directly considered is replacement cost, defined by this model as CPV. The calculation of facility CPV takes into consideration age for the purpose of determining the effect on CPV from inflation. Therefore age is indirectly considered by the CPV model. Location is indirectly considered when used to apply inflation factors for the area in which the facility is located.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The CPV model does not consider varying M&R requirements over the life-cycle of a facility. M&R requirements are considered to be constant throughout the life of a facility.

Criterion 3: Model considers maintenance deferral penalty costs. The CPV model has no mechanism to consider maintenance deferral costs.

Criterion 4: Model uses input data currently available to the USAF. The USAF does not currently maintain plant value in the CPV format for all facilities. The USAF is in the process of updating the replacement values for all facilities, and is using the PRV method to determine plant value for all facilities. Data required by the CPV model could be collected and maintained by the USAF with a minimal effort and expense.

Scoring for CPV Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	2	1	1	1	1	2	1	1	1	4

Percentage of Plant Replacement Value. This model is very similar to the Percentage of CRV model. While the models are evaluated separately in this research, they are usually considered to be a single methodology in the literature. The difference between the two is the method by which plant value is determined. The plant replacement value (PRV) is the "cost to replace a facility with one of equivalent capacity

and function" (Barco, 1994: 29). The PRV model determines facility M&R budget requirements as a percentage of the plant replacement value of the facility inventory.

Annual Facility M&R Budget = X% x PRV of facility inventory

The PRV is usually calculated by multiplying a unit construction cost for the facility type in question, by the units of the facility. The percentage multiplier is determined in the same manner as was discussed in the CPV model above.

Evaluation of Percentage Plant Replacement Value Model.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The only characteristic directly considered is replacement cost, defined by this model as PRV. The model indirectly considers size, facility type, and location (in the form of geographical area unit construction cost factors) through the calculation of facility PRV. Age, climate, type of construction, and condition are not considered.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The PRV model does not consider varying M&R requirements over the life-cycle of a facility. M&R requirements are considered to be constant throughout the life of a facility.

Criterion 3: Model considers maintenance deferral penalty costs. The CPV model has no mechanism to consider maintenance deferral penalty costs.

Criterion 4: Model uses input data currently available to the USAF. The USAF currently maintains the replacement value data required by the PRV model. This model is currently used by the USAF to determine preventive maintenance funding levels.

Scoring for PRV Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	1	2	2	1	1	2	1	1	1	6

Kraft Model. This model was one of the earliest replacement value models. Walter W. Kraft proposed the model in 1950, for use at the University of Oklahoma. Monterecy described it in his dissertation (Monterecy, 1985: 23-25). The original source (Kraft, 1950) was not located, however it is included in the bibliography. It is essentially the same as the CPV and PRV models, except that it used a locally generated maintenance cost factor as follows:

Maintenance Budget = Maintenance Cost Factor x Current Replacement Value

The maintenance cost factor (MCF) is a function of the type of construction used in each facility. Kraft used three categories: wood framed construction; masonry and wood framed construction; and concrete floor construction. The MCF for these three categories was 1.75%, 1.30%, and 1.10% respectively.

This model is intended for use in determining M&R budget requirements for a large inventory of facilities and is not intended to accurately forecast M&R requirements for individual facilities. The use of the three categories in questionable with the large variety of facility construction types today. However, the concept behind the model is adaptable to any facility plant.

Evaluation of Kraft Model.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The Kraft model directly considers replacement cost and type of construction. The Kraft model indirectly considers size, facility type, and location through the calculation of replacement cost. Climate and condition are not considered.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The Kraft model does not consider life cycles of facilities or facility systems.

Criterion 3: Model considers maintenance deferral penalty costs. The model does not have a mechanism to consider maintenance deferral penalty costs.

Criterion 4: Model uses input data that is currently available to the USAF. The Kraft model requires data that the USAF currently maintains, however the maintenance cost factor categories would have to be modified, and appropriate percentage factors would need to be determined.

Scoring for Kraft Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	1	2	2	1	3	2	1	1	1	5

USCG Methodology. The Unites States Coast Guard (USCG) budget methodology is a combination of the SF-based model and the incremental budget model. The USCG currently budgets for M&R using three different classifications. The recurring M&R

budget is defined as the cost of all routine M&R to buildings, piers, floodgates, and runways that are under a $3,000 threshold. It also includes the operations costs such as landscaping, snow removal, and service contracts. The non-recurring M&R budget is major M&R actions that are over the $3,000 threshold. There is also an Acquisition, Construction, and Improvements (ACI) category that is equivalent to the DoD MILCON program. ACI funds could be used for M&R actions in the case of major renovation projects. There is not an ACI funding model; it is justified on a line item basis.

The AFC-30 funding requirements are determined using a standard developed by the Building Owners Management Association (BOMA) 1994 Experience Exchange Report. This is a standard commonly used in the commercial real estate industry. The standard recommends a unit cost ($/SF) for the facility maintenance budget. The amount budgeted in FY97 was $1.51/SF, however the USCG actually received funding at $1.47. The standard was originally $1.37 in 1993, and has been increased each year by 1.1%. Housing recurring M&R funding is determined separately at a flat rate of $2,000 per housing unit.

The AFC-43 budget is determined using a recurring baseline, essentially an incremental budget. The percentage of PRV is also used to influence the amount of funding, the USGC targets for an AFC-43 budget between 1.5% and 2.0%, depending upon the current budget climate. The distribution of the AFC-43 funding is determined using a combination of the facility inventories PRV and the BMAR. A composite factor is multiplied by the funds available to determine the distribution of the AFC-43 budget. The composite factor is calculated as follows:

Composite Factor = Backlog Ratio + PRV Ratio

Backlog Ratio = .25 x (Unit's Backlog/Total Backlog)

PRV Ratio = .75 x (Unit's PRV/Total PRV)

Note that this does not determine non-recurring M&R budget requirements, but actually determines how the available funds will be distributed.

Evaluation of USCG Methodology.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The USCG methodology directly considers size (SF). Replacement cost is indirectly considered, through the distribution of funding and for general targets for AFC-43 funding. The methodology does not consider any of the other characteristics.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The USCG model does not consider life cycles of facilities or facility systems.

Criterion 3: Model considers maintenance deferral penalty costs. The USCG methodology does not have a mechanism to consider maintenance deferral penalty costs.

Criterion 4: Model uses input data currently available to the USAF. The USCG model requires input data that is available, maintained, and in an immediately useable format.

Scoring for USCG Methodology

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	1	3	1	1	1	1	1	1	1	6

Dergis-Sherman Formula. William Dergis and Douglas Sherman developed a formula based model for use at the University of Michigan. They developed the formula to predict facility renewal funding requirements through the life cycle of a facility. The formula they proposed was: Annual Appropriation = 2/3 BV x BA/1275 where BV is building value and BA is building age.

The basic formula assumes that a facility has a life-cycle of fifty years, although the model readily allows for different life expectancies to be used. The variable BA is the building age; it is corrected for either partial (more than 10% of the building value) or complete building renewal. The value 1275 is an age-weighting constant based on the fifty-year life- cycle. The value 1275 is the sum-of-the-years-digits over a 50 year life-cycle (1275 = 1+2+3+.... +50).

The formula assumes that "all construction factors – size, complexity, materials, special facilities, and so on – are conveniently reflected in construction cost" (Sherman and Dergis, 1981: 22). The construction cost is converted into the variable BV, or building value, by inflating "the original cost of each building using a nationally recognized building cost index in order to reflect current year replacement costs" (Sherman and Dergis, 1981: 22). The factor 2/3 is called the "building renewal" constant and is applied because "building renewal ought to cost, on the average, no more than two-thirds of the cost of new construction" (Sherman and Dergis, 1981: 22).

The Dergis-Sherman formula was designed "to be applied to a system of buildings and not just to one building. By applying the formula to a collection of buildings any minor differences that may exist tend to be smoothed and the technique becomes an appropriation or budgeting tool for physical plant needs" (Monterecy, 1985: 126).

Evaluation of Dergis-Sherman Formula Model.

Criterion 1: Model represents those salient characteristics that predict facility maintenance requirements. The formula directly considers replacement cost and age. It indirectly considers facility condition, through the adjustment of building age based on renovation history. Size, age, facility type, type of construction, and location are not considered.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The Dergis-Sherman model incorporates concepts of life-cycle analysis through application of a formula using a sum-of-the-years digits. This simplification spreads the total replacement cost of a facility system over the expected lifetime of the system, with greater proportions of the replacement cost budgeted as the facility ages. This method does not actually predict when the major expenses will be occur; a major system such as the roof is not replaced over the life-cycle of a facility, but is replaced in a single-year. This simplification represents life-cycles in an abstract manner and is best suited for use as a budgeting tool for a large inventory of facilities.

Criterion 3: Model considers maintenance deferral penalty costs. The Dergis-Sherman model does not have any mechanism to consider maintenance deferral penalty costs.

Criterion 4: Model uses input data that is currently available to the USAF. The formula uses replacement value data that is available and maintained, however the building age data used by the formula is not available in a useable format. The building age used by the Dergis-Sherman formula is adjusted based on renovation history. The

USAF maintains building age as the original construction date. Major renovation history is available for the majority of USAF facilities. Generating the adjusted building age data would require modification of existing data into a useable format.

Scoring for Dergis-Sherman Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	3	1	1	1	1	1	2	2	1	5

Preventing Deferred Maintenance Methodology. A model for budgeting for maintenance and capital renewal was proposed by Harvey H. Kaiser in 1995. The purpose of the model is to prevent a backlog of deferred maintenance by developing an appropriate budget. The budget is divided into two separate components. The first component is a maintenance component that consists of "The cost of routine, preventive and emergency maintenance expenditures" (Kaiser, 1995: 29). The second component is a renewal component which is "The cost of renewing facilities to offset deterioration, effects of usage and obsolescence" (Kaiser, 1995: 29). Kaiser specifically excludes costs for operations, alterations and/or remodeling, and reducing deferred maintenance.

As an initial step, Kaiser follows the recommendation of the NRC Building Research Board. That recommendation is to budget between two to four percent of the current replacement value. Because the range between two and four percent is so large, Kaiser recommends separately modeling the maintenance and renewal components. This

also allows for tradeoffs to be made between the two components, when required, because of limited resources.

The budget for the maintenance component is based on:

> Practices and extensive studies of maintenance budgeting and capital renewal by industrial engineers, cumulative data from a variety of non-profit institutions and corporations, and practices applied by the military and other government agencies suggest . . . . Maintenance budgeting is typically in a range of 1 to 1.7 percent of CRV with a minimum recommended "floor" of 1 percent of CRV (Kaiser, 1995: 29).

The renewal component is developed based on life cycle concepts. An annual renewal allowance is determined through a four-step process. The first step is to determine, for each facility, the type of construction, building use, gross area, and current replacement cost. The second step is to develop a building component depreciation table for each building type. For each component, the percentage of gross building value, the life cycle, renewal percentage at the end of life cycle, and component renewal profiles are developed. The third step is to assess the building components, and determine their present condition. The condition of each component is "expressed as a percentage used of the component relative to its life cycle" (Kaiser, 1995: 28). The fourth step is to consider the percentage used of each component and the life cycle profiles to estimate the replacement years. The replacement cost is determined "by using the building replacement cost; the percentage of each building of each component; and the percentage of the component replaced" (Kaiser, 1995: 28). The annual renewal forecast is the sum of the anticipated costs for all the components for the entire facility inventory. The renewal allowance is then expressed as a percentage of CRV. Kaiser suggests a range between 1.5 to 3.0 percent (Kaiser, 1995: 30).

The two components are combined into a final budget. If the overall budget is constrained, then one must tradeoff between the two components. The two methods Kaiser recommends are treating maintenance budgets as a residual of capital renewal, and budgeting for capital renewal as a residual of maintenance budgeting. Neither methods is recommended over the other, although with Kaisers methodology, the process to determine the capital renewal component is better defined than the maintenance component.

This model is a combination of the replacement value and life cycle methodologies. The replacement value is used to determine both the maintenance and capital renewal components. The life-cycle methodology is used to determine the capital renewal component. The capital renewal allowance method used in this model is similar other life cycle methodologies, but differs in its use of a "percentage used" of the replacement cost for each component. This concept incorporates the result of a condition assessment to determine remaining useful life of each component.

<u>Analysis of Preventing Deferred Maintenance Methodology</u>.

<u>Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements.</u> The methodology directly considers replacement cost and facility condition. It indirectly considers age, size, facility type, and type of construction in the determination of building component depreciation. Climate and location are not considered.

<u>Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems.</u> The methodology directly considers life cycles of the major facility systems but not the subsystems.

Criterion 3: Model considers maintenance deferral penalty costs. The methodology has no mechanism to consider maintenance deferral penalty costs.

Criterion 4: Model uses input data currently available to the USAF. The USAF does not have the data required by this methodology and a extensive effort would be required to collect it. The majority of the effort would consist of determining the facility system life cycles and the current condition as a percentage of the replacement value. This data would require a moderate effort to maintain, due to a need to periodically re-inspect the systems to update the condition assessment.

Scoring for Preventing Deferred Maintenance Methodology

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	2	2	2	1	2	1	3	4	1	3

Facilities Renewal Model. This model was described in the article *Facilities Renewal: The Formula Approach* published in a collection titled *Critical Issues in Facilities Management* (Phillips, 1989: 30-46). The first premise of the model is long-range M&R needs should be planned and budgeted using a renewal allowance. The renewal allowance is "the amount to be earmarked each year to offset the aging during that year, and the overall "renewal backlog," the value in current dollars of the unmet renewal requirements represented in the present plant" (Phillips, 1989: 31).

The second premise of the Facilities Renewal Model is a facility consists of systems that have different expected lifetimes. Phillips groups systems into fifty-year and twenty-

five-year categories. This simplification is made because precise life expectancies are difficult to define. The system categories are based on those used in the R.S. Means and Dodge facility cost estimating manuals (Phillips, 1989: 31).

The model focuses on capital renewal or repair budgets, rather that routine or preventative maintenance. Phillips does not consider "systems or elements that require reworking at intervals of substantially less than twenty years . . ." (Phillips, 1989: 31); they are considered to be appropriately funded from separate maintenance and operations funds. This research is focused on models or methodologies that consider both maintenance and repair. However, the logic and method behind this model can also be applied to systems and sub-systems with life-cycles under twenty years. The systems that were considered by Phillips were:

<u>50-Year Systems:</u>

1. Exterior Walls
2. Partitions
3. Conveying Systems
4. Specialties
5. Fixed Equipment
6. PBLG and Fire Protection
7. Electrical

<u>25-Year Systems:</u>

1. Roofing
2. HVAC

The Facilities Renewal Model takes each facility system and "determines the cost per gross square foot of replacing or reworking each system or element" (Phillips, 1989: 31). Phillips used the Dodge and R.S. Means system cost estimating manuals and calculated average cost per SF for each of the facility types in the plant inventory. Phillips also "adjusted them for the types of construction and building sizes . . . and for regional price differentials" (Phillips, 1989: 31).

To determine the annual renewal allowance, Phillips rejected the method of budgeting an equal amount over each year of a building systems lifetime. Instead, an accounting concept similar to depreciation based on the sum-of the-years-digits was used. This concept was taken from the earlier work of Sherman and Dergis. This, in effect, skews the renewal allowance funding, so that a greater annual amount is required as the facility systems age. The following formulas are used to determine facility renewal allowances (RA) for twenty-five and fifty-year systems:

$RA_{\text{25-year systems}}$ = (Building Age/325) x Replacement Cost of 25-year systems

$RA_{\text{50-year systems}}$ = (Building Age/1275) x Replacement Cost of 50-year systems

The values of 325 and 1275 are simply the sum of the years of the systems maximum age for the 25-year and 50-year systems respectively (Phillips, 1989: 35).

The Facilities Renewal Model also considers the effect of previous renovations on the renewal allowance requirements. To accomplish this, the building age is adjusted according to the following formula:

Adjusted Age = (Renovation fraction) x (Years since renovation) + (Un-renovated fraction) x (Age of building)

The Facilities Renewal Model indirectly considers the effect of not funding facility M&R. A facility renewal backlog is calculated by summing the renewal requirements from year 1 to the year in question. If the appropriate renewal funding has not been received in the past, or is not projected to be received in the future years, the projected renewal backlog can be determined. While the model considers this aspect, it does not

have any mechanism to predict increased M&R costs, or premature failures of systems due to inadequate M&R as a result of inadequate funding levels.

Evaluation of Facilities Renewal Model.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The Facilities Renewal model is an extension of the replacement value methodologies. The model directly considers replacement cost, age, size (SF), and facility type. The model indirectly considers type of construction and location in the calculation of the replacement values for facility systems. Climate and facility condition are not considered.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. This model incorporates concepts of life-cycle analysis through application of a formula using a sum-of-the-years digits. This simplification spreads the total replacement cost of a facility system over the expected lifetime of the system, with greater proportions of the replacement cost budgeted as the system ages. This method does not actually predict when the major expenses will be occur; a major system such as the roof is not replaced over the life-cycle of a facility, but is replaced in a single-year. This simplification considers life-cycles in an abstract manner, and is best suited for use as a budgeting tool for a large inventory of facilities.

Criterion 3: Model considers maintenance deferral penalty. The Facilities Renewal Model does not have any mechanism to determine the penalty costs that result from inadequate routine M&R over the life-cycle of a facility.

Criterion 4: Model uses input data currently available to the USAF. The model requires data that is not currently available to the USAF. Specifically, the SF cost data for each facility type would require an extensive effort to compile. Once the data was compiled however, it would only require a low level of effort to maintain.

Scoring for Facilities Renewal Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	3	3	3	1	2	2	1	2	1	3

USAF PRV-FIM. The United States Air Force is currently in the process of implementing the Facilities Investment Metric program (FIM). The FIM is part of an overall USAF facility investment strategy. This strategy involves several investment programs, including preventive maintenance level (PML), facility repair and construction projects, MILCON, and demolition. The overall funding resources are called real property maintenance (RPM) resources. PML and facility repair projects are the two aspects that comprise the RPM requirements considered by this research.

Preservation maintenance level is defined as "the minimum level of maintenance required to sustain the day-to-day operation of the Air Force facilities and infrastructure between periodic repairs and replacement" (USAF, 5). The PML portion of the facility investment strategy is currently calculated at 1% of PRV. Facility repair projects are repair, replacement, and minor construction projects that are accomplished by contract.

Funding for this requirement is called real property maintenance by contract (RPMC) funds. The FIM process is used to advocate funding requirements for RPMC funds.

The FIM process begins at the base level, with Base Civil Engineers identifying all requirements, determining costs, and assigning initial impact ratings. The impact ratings are directly tied to the effect on mission capability. The impact ratings are:

1. Critical: Significant loss of installation/tenant mission capability or frequent mission interruptions; work arounds are continually required causing extensive disruption and considerable degradation of mission effectiveness.

2. Degraded: Limited loss of installation/tenant mission capability; work arounds to prevent mission disruption and degradation are often required.

3. Minimal: Marginal or no adverse impact to installation/tenant mission capability; work arounds to prevent mission disruption and degradation are seldom required.

Installation commanders validate the requirements and impact rating; MAJCOMs take the requirements and impact ratings and group them according to mission areas.

The mission areas are determined according to facility types, as identified by USAF real property category codes. FIM defines four mission areas:

1. Primary Mission: Facilities and infrastructure integral to the installation's/tenant's primary mission.

2. Mission Support: Facilities directly supporting the installation's/tenant's primary mission.

3. Base Support: Facilities not integral to the primary mission, but necessary to keep the installation/tenant functioning properly.

4. Community Support: Facilities supporting the base community, base personnel, or facilities that do not fall under any of the other mission areas.

Once all the requirements are identified, cost-estimated, and assigned a mission area and impact rating, the FIM process organizes the requirements into a matrix:

Figure 2. Mission Area Matrix (from USAF FIM Executive Overview, 4)

	IMPACT RATING		
Mission Area	Critical	Degraded	Minimal
Primary Mission			
Mission Support		Costs of Unfunded	
Base Support		Requirements	
Community Support			

The MAJCOMs calculate Facility Investment Indices (FIIs), which are the "total facility requirements for all facilities in a particular mission area category, divided by the plant replacement value for that mission area" (USAF FIM, 1997: 4). The FIIs can be calculated for base, MAJCOM, and USAF level mission areas. The FIIs and the mission area matrix are used to determine the USAF investment strategy.

There is not an actual model where M&R funding levels are determined through the input of data and output of funding levels.

> Once installations/tenants array the requirements in the FIM Matrix, the profile of requirements will help the Air Staff develop an investment strategy. The Air Force Corporate Structure will then determine a level of RPMC investments based on the most urgent needs of the Air Force (USAF, 1997: 5).

The FIM process provides a method to connect M&R requirements to mission requirements. The FIIs are a metric that is used to evaluate the health of the facility inventory. The FIIs provide information to help allocate limited funding to mission critical areas, and provide feedback concerning the effectiveness of the investment strategy. The FIIs are calculated at the beginning and end of funding cycles, which provides information as to the results of the investment strategy.

While no formal inspection and condition assessment program is prescribed by the FIM process, the use of FIIs to allocate funding, help ensure that USAF installation

commanders will accomplish the necessary inspections to identify all requirements. The levels of investment are determined using the FIIs; therefore, the more requirements which are identified and validated, the larger the FII, and the greater chance funding will be obtained.

Evaluation of USAF PRV-FIM Methodology.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The USAF PRV-FIM methodology directly considers replacement cost and facility condition. Size, facility type and location are indirectly considered through the calculation PRV. Age, type of construction,, condition assessment, and climate are not considered.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The USAF PRF-FIM methodology considers life-cycles of facilities and facility systems in an indirect manner. Life-cycles concepts are used to predict remaining useful life of facilities and systems; however it is based on the professional judgement of inspectors and project planners, and done for the short-term horizon. No mechanism is used to predict repairs or replacement requirements over the life-cycle of a facility.

Criterion 3: Model considers maintenance deferral penalty costs. The USAF PRV-FIM methodology has no mechanism for considering maintenance deferral penalty costs.

Criterion 4: Model uses input data currently available to the USAF. Once the FIM process has been implemented USAF-wide in November 1997, the required input

data will be available and maintained, and in an immediately useable format. This rating is by default, because the USAF has decided to implement the program.

Scoring for USAF PRV-FIM Methodology

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	1	2	2	1	1	2	3	2	1	6

Square Foot Based Model. The Square Foot (SF) based model is a very simple model which uses only the SF of the facility inventory to determine M&R requirements:

M&R Budget = SF of Facilities x Cost Factor

The cost factor that is used can be determined in a variety of ways. The most common method of determining the cost factor is the use of historical data. Sources of this data include the Building Owners and Managers Association International and R.S. Means and Company. A recent research effort at the University of New Brunswick proposed an expert system that predicts operating and maintenance costs per SF (Christian and Pandeya, 1997).

The SF based model is meant to be applied to a large number of facilities. Its strengths are simplicity and ease of application; however, it does not consider the range of differences between facilities that may impact the M&R requirements. Another difficulty is that historical M&R cost data does not reflect the level or quality of M&R standards. Different organizations set different M&R standards; it is questionable

whether cost data can be applied across the board. In addition, the amount spent on M&R historically is often driven by availability of funding rather than M&R requirements.

Analysis of Square Foot Based Model.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The model directly considers size of the facility inventory (SF) and does not consider any of the other characteristics.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The SF-based model does not consider facility or facility system life cycles.

Criterion 3: Model considers maintenance deferral penalty costs. The model does not have a mechanism to consider maintenance deferral penalty costs.

Criterion 4: Model uses input data that is currently available to the USAF. The SF-based model uses data that is available, maintained, and in an immediately useable format by the USAF.

Scoring for Square Foot Based Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
1	1	3	1	1	1	1	1	1	1	6

Incremental-Budget Model. One of the most common budget tools is the Incremental-Budget model, also referred to as historical budgeting, or ramping. As opposed to a zero-based budget, which must be re-justified each year, the Incremental-Budget model is based upon the previous M&R budgets. The Incremental-Budget model determines annual M&R budget requirements by incrementing the previous year's budget by a factor. This factor is generally a positive increment, related to inflation (DoD, 1989: 6) (Barco, 1994: 29) (CERF, 1996: 16). While it is not discussed in the literature, in the current budget climate of reduced funding, it is possible that the factor used is actually negative. A negative factor is not related to inflation, but rather the need to reduce spending.

The incremental budget model is widely used in public organizations because of its simplicity. It is also well suited for use in the constrained budget environment in which public organizations operate. A common perception is "the effort and expense involved in developing more accurate LOI estimates do not seem justified in light of the competition for funds" (CERF, 1996: 17). The reality of the budget situation dictates that M&R budgets are determined by the amount of money centrally available to the overall organization. This is often determined based on the previous year's funding and projections for future year funding.

Criticism of the Incremental-Budget model is very evident in the literature. One drawback is if previous budgets have been inadequate, then future budgets will be as well. This results in chronic, long-term underfunding (CERF, 1996: 16). A major fault with this method is that "after several years this model typically loses any correlation

with the actual M&R requirement, and tends to rely on the base to justify itself . . ." (Barco, 1994: 29).

Analysis of Incremental-Budget Model.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The Incremental-Budget Model does not consider any of the eight facility characteristics.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The Incremental Budget Model does not consider life-cycles of facilities.

Criterion 3: Model considers maintenance deferral penalty costs. The Incremental Budget Model has no mechanism that considers maintenance deferral penalty costs.

Criterion 4: Model uses input data currently available to the USAF. The Incremental-Budget model uses previous annual budgets as input data. This data is available, maintained, and in an immediately usable format.

Scoring for Incremental-Budget Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
1	1	1	1	1	1	1	1	1	1	6

U.S. Army MRPM. The U.S. Army Construction Engineering Research Laboratories developed the Maintenance Resource Prediction Model (MRPM) in 1991. The development of MRPM was a seven-year research effort. The objectives of the

research were to "develop a comprehensive database containing M&R cost data for Army facilities and prediction models for outyear maintenance requirements" (Neely et al, 1991: 6). The foundation of the MRPM model is the maintenance task databases. The MRPM is a computer-based model that predicts life-cycle maintenance costs for buildings, based on the databases.

The maintenance task databases were developed to include "all maintenance work required over the life of every component that could be found in buildings constructed by private industry and government agencies" (Neely and Neathammer, 1991: 311). The databases were built consisting of all the components used in Army buildings and all the tasks that would be preformed to maintain the components. The list of components was developed using the guidelines of the UNIFORMAT divisions (Neely et al, 1991: 16).

For each component, all maintenance tasks that could be required during the component life were developed. A task is defined as "the work performed on a component by a single trade" (Neely et al, 1991: 16). For each task, frequencies of expected occurrence were developed. Three frequencies were used: high, average, and low. Average frequency is the most likely time of occurrence, low is the latest time of occurrence, and high is the earliest time of occurrence. Finally, for each task, material quantity and costs, labor hours, equipment hours, and crew size were determined. This information was developed using DoD engineered performance standards manuals and Corps of Engineers cost-estimating manuals (Neely and Neathammer, 1991: 311).

After developing the maintenance task database, all buildings were modeled at Forts Bragg, Leonard Wood, Devens, and Ord. At each of these installations, an on-site inspection of each building was accomplished, and a thorough component inventory was

developed. This allowed each building to be modeled using the maintenance task databases. The MRPM computer system "was used to generate resource requirements for the first 120 years of building life. The individual buildings were combined into . . . 34 category groups, and all resources were averaged to obtain average resource data at several levels of detail" (Neely and Neathammer, 1991: 313).

The MRPM system can predict annual maintenance requirements over 120 years of building life given five different levels of data (Neely and Neathammer, 1991: 314):

1. Predict annual cost when only the building SF area is known.
2. Predict annual cost when building SF area and current functional use are known.
3. Predict annual cost when building SF area, current use, and age of the facility are known.
4. Predict the total labor hours, equipment hours, labor cost, material cost, and equipment cost when building SF area, current use, age, and average cost for labor and equipment per hour are known.
5. Predict the total labor hours, equipment hours, labor cost, material cost, and equipment cost for each trade or shop when building SF, current use, age, and individual shop costs for labor and equipment per hour are known.

Another option is to use the maintenance task database to model all the individual components in each facility. This would be extremely labor intensive, and represent the opposite extreme from using the MRPM given only SF data. For the purposes of this analysis, the MRPM model will be separately evaluated as two models. The first will assume an application of the MRPM given a full facility component description. The second will assume an application of the MRPM model given facility area, functional use, and age.

Evaluation of MRPM Facility Component Description Model.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The facility component description version of the MRPM model directly considers replacement cost, age, size, facility type, type of construction, and location. Replacement cost is not considered in the context of the facility as a whole, but as individual systems and subsystems. Location is considered through the application of local cost factors; the default values used by the MRPM models are for the Washington D.C. area. Climate and facility condition are not considered.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The facility component description MRPM model is directly based upon the life-cycles of facility systems and subsystems. At the basic level, the model predicts maintenance and repair requirements of individual components, and them combines the existing components of a facility to determine overall facility requirements.

Criterion 3: Model considers maintenance deferral penalty costs. The MRPM model is based upon life-cycle maintenance costs using low, average and high frequencies of maintenance task occurrences. There is not a mechanism to consider the effect of inadequate maintenance on the task occurrence frequencies. The model assumes the maintenance will be done at the appropriate times.

Criterion 4: Model uses input data that is currently available to the USAF. The facility component description MRPM model is not practical for use as a macro-level budgeting tool. Gathering and maintaining the data required for a single facility would require an extensive effort. Gathering the data for all the facilities in the USAF inventory

is clearly not practical. This model is meant to be applied in "life-cycle cost analyses for the design of new facilities" (Neely et al, 1991: 5).

Scoring for MRPM Facility Component Description Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	3	3	3	1	3	3	1	5	1	1

<u>Evaluation of MRPM Area-Use-Age Model.</u> This is the analysis of the MPRM model that predicts life-cycle maintenance costs given information on facility area, functional use, and age.

<u>Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements.</u> The MRPM Area-Use-Age model directly considers age, size, and facility type. Location is considered through the application of local cost factors; the default values used by the MRPM models are for the Washington D.C. area. Replacement cost and type of construction are indirectly considered. This was accomplished through the detail modeling of all facilities at four installations, and the determination of the average resource requirements given the area, functional use, and age data. Climate and facility condition are not considered.

<u>Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems.</u> This model determines the average resource requirements given the area, functional use, and age data, based upon modeling the facilities at four installations and averaging the results. The basis of the

determination of maintenance requirements is life-cycle requirements for facility systems and subsystems; however, the MRPM Area-Use-Age model considers this in an indirect manner though the averaging process which was used to determine requirements give area, use, and age data.

Criterion 3: Model considers maintenance deferral penalty costs. The MRPM model is based upon life-cycle maintenance costs using low, average and high frequencies of maintenance task occurrences. There is not a mechanism to consider the effect of inadequate maintenance on the frequency of task occurrences. The model assumes the maintenance will be done at the appropriate times.

Criterion 4: Model uses input data that is currently available to the USAF. The data required by the MRPM Area-Use-Age model is available and maintained by the USAF; however, Army facility codes are not directly compatible with the USAF category codes. A thesis by Harold Keck, found that 59 of the 504 USAF building categories had no equivalent code used by the MRPM model (Keck, 1992: 31-32). Therefore, the data is available and maintained, but not in an immediately useable format.

Scoring for MRPM Area-Use-Age Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
2	3	3	3	1	2	3	1	2	1	5

U.S. Army ISR Methodology. The U.S Army currently uses the Installation Status Report (ISR) to provide an objective assessment of the status of Army installations. The ISR consists of three parts: infrastructure (ISR Part I), environment (ISR Part II), and services (ISR Part III). The ISR rates installation status on a four-point scale, called a C-Rating. The C-Rating is also used by the Army to describe the status of personnel, training, equipment status, etc.

ISR Part I divides facilities into five areas: Mission Facilities, Strategic Mobility Facilities, Housing, Community Facilities, and Utility Systems. The areas are further broken down into a hierarchy that ends in 215 individual Facility Category Groups (FCGs). At each installation, the FCGs are rated for quantity and quality, using the C-Rating scale.

The rating for quantity is based upon comparing installation requirements against the quantity of on-hand permanent or semi-permanent facilities. The rating for quality is based upon physical condition of the facilities in the FCG, as determined by condition assessments of each facility, against Army condition standards. These FCG quality and quantity ratings are rolled up into a FCG rating at the US Army Major Command level (MACOM) and a FCG rating for the entire U.S. Army.

The rating process begins at the installation level, with facility users accomplishing the condition assessments. The conditions of the major facility components are rated according to individual standards booklets for the facility type being inspected. The booklets provide written and graphical standards that are used to objectively evaluate component condition. The condition of each component is rated green, amber or red. A green rating means the component meets Army standards; amber and red are substandard,

with red being the worst rating. The ratings are recorded on a facility worksheet and the overall quality C-Rating for a FCG is calculated from the distribution of the color ratings for all the facilities in the same FCG.

The ISR provides U.S. Army decision-makers with information concerning the quantity and quality of their installation infrastructure. The ISR also has a Decision Support System (DSS) that estimates the resources required to improve and sustain the installation's infrastructure and facilities. The methodology used by ISR is a macro level budget tool, not intended for application to individual facilities. It is appropriately applied at the MACOM and HQDA level. The resource requirement models used by the ISR DSS estimate costs for new construction, renovation, and sustainment.

New construction cost estimates are used to improve the C-Rating for quantity in a given FCG. Because new construction is not considered in this research, the models for new construction will not be discussed further. Renovation cost estimates are applied to determine the funding requirements to bring existing facilities, which are rated amber or red, up to green. Sustainment costs include routine maintenance and major component repair/replacement that are required to sustain a facility at it current condition.

The estimation of sustainment and renovation costs is accomplished by applying unit cost factors. Sustainment and renovation cost factors are determined differently. Sustainment cost factors are based upon the Army MRPM model. The renovation cost factors are determined through five different methods. Describing the five methods is beyond the scope of this analysis; however, they rely upon the use of empirical data from past Army renovation projects when possible (USACEAC, 5). The process of determining renovation cost factors is actually a dynamic process; the U.S. Army Cost

and Economic Analysis Center (USACEAC) is constantly updating and refining the process as more empirical data is received.

Evaluation of U.S. Army ISR Methodology.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The Army ISR methodology directly considers facility condition through the application of its condition assessment and rating, which determines the subsequent sustainment and renovation requirements. Facility type is directly considered through the use of cost factors that depend on the FCG. Size is directly considered when unit cost factors are used. Age, type of construction, and replacement cost are indirectly considered through the use of the MRPM model for sustainment costs. Climate is not considered.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The ISR Methodology considers life-cycles of facilities and their systems in an indirect manner. The unit cost factors that are used for determining sustainment costs come from the MRPM model, which also receives a score of two for this criterion.

Criterion 3: Model considers maintenance deferral penalty costs. The ISR Methodology has no mechanism to consider maintenance deferral penalty costs.

Criterion 4: Model uses input data that is currently available to the USAF. The data required by the Army ISR Methodology is not available to the USAF. The required data consists of basic real property inventory data and the annual condition assessments. The condition assessments are very simple and standardized and would require minimal effort and expense to accomplish. The inventory date would require some minor format

modification to overcome the differences between the Army and USAF real property data structures.

Scoring for Army ISR Methodology

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
2	2	3	3	1	2	3	3	2	1	4

UNIFORMAT Methodology. The Uniform Building Component Format (UNIFORMAT) methodology is a life-cycle approach to predicting long range M&R needs. Eric Melvin described it in *Plan. Predict. Prevent. How Reinvest in Public Buildings* (Melvin 1992: 48-53). As described by Melvin, it is more of a framework for developing a life-cycle based model than a distinct model. It allows for flexibility in determining how far down the facility system hierarchy to model, and whether or not to incorporate condition assessment data.

A fundamental aspect of a life-cycle methodology is a uniform structure that organizes the life-cycle information and repair/replacement cost data. Several possible structures exist, and the choice depends upon the level of detail that is required. An option proposed by Melvin, are the Uniform Building Component Format (UNIFORMAT) systems developed by the American Institute of Architects and the General Services Administration. UNIFORMAT is broken into levels; Levels 2 and 3 are listed in the Appendix. There is also a fourth level of detail that could be used if greater

resolution is desired, although higher data requirements accompany the greater resolution.

The UNIFORMAT building component structure has a straightforward relationship with the MASTERFORMAT system, which is widely used by major cost guides such as R.S. Means and Dodge. The relationship is shown in Appendix A. Therefore, the cost data for each UNIFORMAT facility component can be readily obtained.

The next step is to assign life expectancies values to each component. If historical data is available, that is preferable. Otherwise, an accepted source of life expectancies is used. Melvin presents mean-life cycle data by components, which was developed through a survey of USAF facility engineers at eight USAF bases in the CONUS. These values are listed in Appendix A. Predictions of life expectancies assume regular maintenance will be accomplished (Melvin, 1992: 50). The estimated replacement year is projected by adding the life expectancy to the year the component was installed or last replaced. Optionally, condition assessment can be accomplished to determine if a component is likely to fail before, or even after, its anticipated replacement date.

Melvin recommends using square foot estimates for predicting future component replacement cost. Such estimates are available in several sources, such as the annual publication of *the R.S. Means Repair and Remodeling Cost Data*. The model then predicts long-range M&R costs for each building by breaking the life of a facility into time intervals, such as five-year intervals, and then uses the component age and life-expectancy data to predict in which intervals the components will require replacement or renewal. The costs for a time interval are simply the sum of the replacement costs for the

components that are expected to require replacement during the interval. The results for each facility are summed to determine the overall facility inventory requirements.

This methodology relies on the law of averages and is meant to be applied to a large inventory of facilities, not to individual facilities. It is simple to apply and the component categories and cost data are based upon widely accepted industry standards. The model is easily implemented using a spreadsheet.

Evaluation of UNIFOPRMAT Methodology.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The UNIFORMAT model directly considers replacement cost, age, size, facility type, and type of construction in the determination of component life expectancies and renewal costs. Climate and facility condition are indirectly considered if the life expectancies are modified. Location is also indirectly considered if renewal costs are modified according to local cost factors.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The UNIFORMAT structure considers life-cycles of the facility systems and subsystems. The level, which is actually modeled, depends upon the desired resolution however.

Criterion 3: Model considers maintenance deferral penalty costs. The model assumes regular annual maintenance and does not have a mechanism to consider the effect of maintenance deferral penalty costs.

Criterion 4: Model uses input data currently available to the USAF. The UNIFORMAT model requires input data that is not currently available. The initial effort

to gather data to implement the model would require an extensive effort. Maintenance of the data would require a low level of effort and expense after the initial effort.

Scoring for UNIFORMAT Methodology

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	3	3	3	2	3	2	2	5	1	3

Stanford Model. This model was developed for use at Stanford University. Hutson and Biedenweg describe the model in the article *Before the Roof Caves In: A Predictive Model for Physical Plant Renewal*, published in the collection: *Critical Issues in Facilities Maintenance* (APPA, 1989: 12-29). The model is a "quantitative method developed at Stanford University that programmatically addresses the short- and long-term needs of the physical plant" (Hutson and Biedenweg, 1989: 12-13). The central premise of the Stanford model "is that predictable cycles exist for facility renewal and replacement" and that facility systems and subsystems "have identifiable life expectancies and will require replacement after predictable periods of time" (Hutson and Biedenweg, 1989: 14).

The foundation of the Stanford Model is a "framework" consisting of a database that models the existing facility plant at Stanford. The facility subsystems, facility types, subsystem life cycles, subsystem replacement costs, and date of facility construction define the framework. The framework is essentially data that describes the facility plant, the expected performance of the plant, and expected costs of renewal over time. A

simple computer model is used to perform the calculations that generate the expected costs.

The first step in the model is to define the facility subsystems. Facility subsystems are divided into thirteen classes: foundations and major vertical, floor, and roof structures; roofing; exterior cladding; interior finishes, elevators, plumbing, HVAC-moving; HVAC-static; fire protection; and special equipment and miscellaneous (Hutson, and Biedenweg, 1989: 16). The model assumes that the functional use of a facility has an impact on the subsystem design and resulting cost. The model identifies five categories of facility types at Stanford that have significantly different subsystem designs. The categories are: research/teaching laboratories; offices/classrooms/athletics/libraries; patient care; storage buildings and others with minimal usage; and residences.

Subsystem life-cycles were defined for each of the thirteen subsystems. The process by which the life-cycles were defined consisted of consulting various professional handbooks and analysis of historical experience at Stanford. A Delphi technique was used to poll experts (who the experts were, was not disclosed) and the result was a set of pessimistic, likely, and optimistic life-cycles for each subsystem. An underlying assumption was the subsystems "had been and would continue to receive a normal level of maintenance" (Hutson and Biedenweg, 1989: 18).

The Stanford Model defines an average renewal/replacement cost for each building subsystem by facility type. The costs are defined on a dollar per square foot basis. For example, the replacement cost for roofing on residential building was $4.10 per SF and $3.20 per SF for laboratory buildings. The costs were determined using various construction cost indexes and a historical database of Stanford construction cost data.

The construction costs were increased by 130% to reflect the assumption that replacement costs for individual subsystems is higher than new construction costs.

The final data consideration is the date of facility construction. The assumption is that the construction date of the facility is the starting point for the subsystem life-cycles. The construction date is defined in an "age cohort", which is a series of five-year groupings, beginning with the oldest facility in the inventory (1891 in the case of Stanford). The issue of major renovations is dealt with by re-establishing the age cohort at the remodeling date (Hutson and Biedenweg, 1989: 20).

The framework of data was compiled to represent the expected performance and renewal cost of the facility plant. A simple computer model was developed to "simulate the wear-out and resulting replacement cost" (Hutson and Biedenweg, 1989: 21) of the facility plant using the framework of data. The model operates by summing all expected repair/replacement requirements in five years periods. The requirements are determined for each facility and combined into an overall plant forecast. The model allows for a forecast of repair/replacement requirements by subsystem type as well.

The Stanford model predicts long-term facility renewal requirements. It does not have a mechanism for determining appropriate preventive maintenance requirements. It is intended to be applied to a large inventory of facilities, and not to predict M&R requirements for a single facility.

<u>Analysis of the Stanford Model.</u>

<u>Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements.</u> The Stanford Model directly considers replacement cost, age, size, and facility type. The Stanford Model indirectly considers type of construction and

location in the determination of estimated subsystem replacement costs. Facility condition is indirectly considered; only the effect of a major renovation on the facilities age cohort is considered. Climate is not considered.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The Stanford Model directly considers life cycles of facility systems, but does not consider subsystems.

Criterion 3: Model considers maintenance deferral penalty costs. The model does not predict preventive maintenance requirements and does not consider the effects of inadequate preventive maintenance on maintenance deferral penalty costs. The Stanford Model assumes that a "normal" level of maintenance has been accomplished in the past, and will continue to be accomplished.

Criterion 4: Model uses input data currently available to the USAF. The Stanford model requires input data that is not currently available for USAF facilities. The facility types used by the Stanford model were developed for a specific university plant, and would require modification for USAF use. Likewise, the appropriate subsystem life cycles and replacement costs would need to be developed. This would require an extensive effort, but would only require a moderate effort and expense to maintain after the initial effort.

Scoring for Stanford Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	3	3	3	1	2	2	2	4	1	3

BUILDER. The U.S. Army Construction Engineering Research Laboratories (USACERL) is developing the BUILDER Engineered Management System (EMS). As the term management system implies, BUILDER does not just predict M&R requirements; BUILDER is a decision support tool that helps facility managers.

Building M&R requirements are modeled through a process of inventory, inspection, condition assessment, deterioration modeling, condition prediction, and M&R planning. A building is modeled using a hierarchy that breaks a building into 12 systems. The systems are site; structural; roofing; exterior circulation; exterior closure; interior construction; plumbing; HVAC; electrical; fire suppression; conveying; and specialties. Each system is further broken into different components. Each component is classified according to a material category or an equipment category. Finally, the components are further divided in subcomponents. An example of this hierarchy is:

System	Component	Material Category	Subcomponent
Interior Construction	Interior Door	Wood	Door Frame

The first step in implementing BUILDER is to accomplish a facility inventory and enter the information into the BUILDER database. The inventory establishes the building/system/component hierarchy that is the foundation of the BUILDER model. The inventory includes information on what buildings are on the installation, the systems in those buildings, the components contained in those systems, and the types, sizes, and materials of those components. The inventory provides the basic information needed to

determine inspection requirements, component condition prediction, and M&R planning and budgeting.

The next step is the inspection and condition assessment process. The intent is "to collect the minimum amount of data necessary to define the condition of a building and its components, develop annual and long range work plans and budgets, and formulate M&R budgets." (Uzarski, 1997: 5). Sampling theory is used to determine the minimum level of inspection required accomplishing those goals. The sampling occurs at the component level. BUILDER determines the appropriate samples based on the inventory data. "Within each sample, all of the applicable subcomponents are inspected for the presence of applicable distress types, severity, and densities" (Uzarski, 1997, 5).

There are 21 distress types, including animal/insect damage, blisters, cracks, corrosion, holes, moisture/debris contaminated, etc. The severity is rated low, medium, or high. Density is determined according to the "amount of the particular distress and is expressed as a percentage. To simplify the inspection process, density is fixed to give ranges: <1%, 1-10%, 11-25%, 25%-50%, and >50%" (Uzarski, 1997: 8). A sample inspection result for cement flooring could be 25-50% of the cement floor has low severity cracking.

A key aspect of the BUILDER model is the use of condition indices (CI). The CI is a scale from 0 to 100, with 0 representing failed and 100 being "free of observable distress". BUILDER takes the inspection condition assessment results for each subcomponent and calculates a subcomponent CI. Each distress results in a "deduct value" which reduces the CI from the value of 100. Multiple distresses are combined such that "as additional distress types and/or severity levels occur in the same sample

unit, the impact of any given distress on the condition rating becomes less" (Uzarski, 1997: 8). This prevents the CI from becoming negative in the case of multiple distress types. A process of "rolling up" occurs that takes the subcomponent CI rating and calculates sample unit CI rating (SUCI), which in turn is combined into component section CI (CSCI), building component CI (BCCI), system CI (SCI), and finally a building CI (BCI). The "rolling up" algorithm is fairly complex, but is basically a process of applying weighting factors (Uzarski and Burley, 1997, 9-10).

Once the building inventory has been inventoried, inspected, and CI ratings have been calculated, condition prediction can be accomplished using BUILDER. This is accomplished using deterioration curves. For each component modeled by BUILDER, a deterioration curve has been developed to predict likely CI values over time. Likewise, cost curves exist which predict "costs to repair" at various CI levels. These curves were developed using the professional experience of the USACE engineers, historical data, manufacturer recommendations, and accepted construction standards such as R.S. Means.

While default cost curves exist in BUILDER, the user may modify them as necessary. For example, if M&R work is accomplished by contract with pre-determined costs, then those costs can be used to modify the default cost curves in BUILDER. The deterioration curves can also be modified. As BUILDER is used over a period of time, the location specific inspection results are tracked and the deterioration curves can be modified to accurately model the actual performance of components at a certain location. For example, due to severe climate and/or environmental conditions at a location, building roofs may deteriorate at a greater rate than predicted by the default curves. The

actual performance data over time could be used to develop custom deterioration curve for that location.

The M&R planning component of BUILDER offers the decision-maker several tools. BUILDER models the current condition and the predicted condition of the facility inventory. This can provide a M&R budget to deal with all predicted requirements. In the case of limited funds, BUILDER leads the DM through a step-by-step process, eliciting input concerning issues such as priorities, allowable CI/degradation thresholds, and budget limits. From that information, BUILDER creates multi-year M&R plans. BUILDER can create multiple plans allowing the DM to consider multiple "what-if" scenarios.

Evaluation of BUILDER.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. BUILDER directly considers replacement cost, age, size, facility type, type of construction, location, and age. These characteristics are directly considered in determining the deterioration and cost curves. Climate is indirectly considered. In the case of HVAC, there are zones based on climate, which affect the life expectancies of HVAC components. BUILDER can incorporate inspection data, over time, into modified deterioration curves for each location. Thus, location specific effects from climate are represented.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. BUILDER directly considers life-cycles of facility systems and subsystems (defined as component in

BUIILDER). As discussed above, the use of life-cycles is the foundation of the BUILDER model.

Criterion 3: Model considers maintenance deferral penalty costs. BUILDER directly considers maintenance deferral penalty costs that may result from funding M&R at an adequate level. BUILDER also has the capability to consider differences between continuous underfunding and one-time failures to fund. This is accomplished using the deterioration and cost curves to illustrate penalty costs. These penalty costs are additional "costs to repair" which are incurred when repair actions are not taken at the most cost effective point of deterioration.

Criterion 4: Model uses input data currently available to the USAF. BUILDER requires inventory and inspection data that is not currently available to the USAF. The initial effort to enter the inventory information in the required format would require an extensive effort. The initial inspection data would also require an extensive effort, although BUILDER minimizes the data requirements as much as possible, while maintaining statistical validity. Subsequent inspections would be required at a frequency ranging from one to three years, depending upon the particular components.

Scoring for BUILDER Model

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	3	3	3	2	3	3	3	5	3	3

AME Methodology. Applied Management Engineering (AME) is a company that provides a variety of M&R services, including condition assessment and long term maintenance and repair planning. AME has two M&R planning and budgeting software packages. The Facility Condition Information Systems (FCIS) is a condition assessment-based program that "develops current, annual, and long range maintenance requirement plans and reports" (AME, 1997: WWW). The Backlog and Funding Projection Model (Rush model) predicts levels of BMAR based on projected funding levels, or conversely, predicts necessary funding levels to achieve a certain BMAR level.

The FCIS is a proprietary software package, and AME would not provide specific details on the program's algorithms. However, FCIS and the Rush model are based upon the approach to M&R planning described in the book titled *Managing the Facilities Portfolio: A Practical Approach to institutional Facility Renewal and Deferred Maintenance*. The book was written by AME and Sean C. Rush.

Short-range renewal needs are considered to be efforts towards reducing deferred maintenance backlogs (BMAR) to "an acceptable, predetermined level" (AME, 1991: 39). Determining short-term requirements is accomplished through a comprehensive inspection of the facility inventory, followed by identification and tabulation of the deficiencies. Long-term renewal requirements are estimated through a combination of condition assessment and system life cycle concepts.

There is a six-step process by which long term renewal needs are determined. The first step is to categorize the types of facilities in the inventory. The facility types determine the cost per SF for facility system repair/replacement. The next step is to develop a list of components that will be renewed. The suggested categories include

exterior walls, roofs, floors, ceiling, interior walls, windows, doors, HVAC, plumbing, electrical, fire protection, and elevators. Then, for each component class, a list of construction or material types is developed. Different material types for a given component will have different life expectancies and renewal costs. For each component the average useful life is estimated. Finally, the unit renewal cost for each component is determined (AME, 1991: 50-51).

Once the basic information above has been determined, facility inspections and condition assessments are accomplished. For each facility, the components are assessed to determine the material type and estimated remaining useful life (years to renewal). Estimates on years to renewal are made in five-year increments, because exact estimates are not considered realistic. Using the estimates on remaining life, and the life cycle of each component, renewal periods and the renewal cost are predicted over the facilities life for each component.

The short- and long-term renewal models are based upon the assumption that the BMAR will be reduced to zero within five years. It is recognized that this is not a fiscally reasonable assumption. The Backlog and Funding Projection Model (Rush model) was created to predict the level of BMAR, given a certain funding level. It can also project the required funding level given a desired BMAR. The Rush model is based on the concept of facility reinvestment rate, which is simply the renewal funding, divided by the current replacement value (AME, 1991: 63-76).

The backlog projection model uses the following formula:

$B_n = (B_{n-1})(1 + I_n + D_n) + (V_v)(P_n) - F_n$

Where: B_n = Backlog at end of year n
V_n = Current replacement value at end of year n
$V_n = (V_{n-1})(1 + I_n + G_n)$
I_n = Inflation rate in year n
D_n = Backlog deterioration rate in year n
P_n = Plant deterioration rate in year n
G_n = Average plant growth rate in year n
F_n = Planned funding in year n

To determine required funding to achieve a desire backlog, the formula is rearranged:

$F_n = (B_{n-1})(1 + I_n + D_n) + (V_v)(P_n) - B_n$

This methodology incorporates aspects of the condition assessment, lifecycle, and replacement value methodology categories. It is applicable to a large inventory of facilities because of its reliance on estimations of component remaining useful life and overall component lifecycles. It also relies heavily on the experience and professional judgement of the personnel who apply this methodology. Other methodologies are very similar to the AME methodology are used by several organizations offering M&R planning services. The key service these organizations really offer is the experience and professional judgement in applying the fairly standard methodology.

Analysis of AME Methodology.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The AME methodology directly considers replacement cost, size, facility type, and type of construction in determining the renewal cost of facility components. Age and facility condition are directly considered in determining remaining

useful life and lifecycles of components. Location is indirectly considered in the cost calculations, through the use of area construction rates. Climate is not considered.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The AME methodology directly considers life-cycles of the facilities systems, but not subsystems.

Criterion 3: Model considers maintenance deferral penalty costs. While the Rush model does predict BMAR based upon the projected renewal finding level, it does not consider the penalty costs of inadequate M&R funding. In other words, if M&R is not accomplished, the requirement will be carried over into the future, but no mechanism exist which reflects increased rate of deterioration based on lack of M&R.

Criterion 4: Model uses input data currently available to the USAF. The AME methodology requires data that is not available, and would require extensive effort to collect. The initial condition assessment, determination of component categories, life-cycles, and renewal costs all require an extensive effort. Maintenance of the data would require an extensive effort, with annual to semi-annual periodic inspections to re-assess the facility and facility component conditions.

Scoring for AME Methodology

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
3	3	3	3	1	3	2	3	4	1	2

U.S. Navy Long Range Maintenance Planning. The United States Navy uses two distinct methods to determine facility M&R requirements. Routine and preventive M&R are accomplished by contract, through Public Works Centers (PWC). The recurring preventive maintenance program is based upon manufacturer maintenance recommendations. A contract, or maintenance service agreement, is negotiated with the contractor, and the contract determines the funding level for recurring preventive maintenance.

The foundation of the process of determining non-recurring maintenance and repair requirements is the Navy Long Range Maintenance Planning (LRMP) management system. The LRMP is:

> a management system based on comprehensive facility inspections and accurate cost estimates. Long Range Maintenance Planning provides the activity with systematic, in-depth documentation of maintenance and repair requirements forecasted over a multi-year planning cycle. The activity uses this information to formulate funding strategies and to allocate resource dollars. . . . The computer is used as a compact filing system to organize pertinent facility data. Using the computer the activity and PWC facility mangers may generate funding and execution plans. . . It allows analysis of the needed repairs and identification of critical conditions requiring immediate attention (U.S. Navy LRMP Manual, 3).

The LRMP is a condition assessment based methodology. Trained personnel accomplish the facility inspections and condition assessments. The inspections are recurring; they are done annually or tri-annualy depending upon the facility and the types of equipment and systems present. The LRMP maintains inventory information that is used to generate a master schedule of inspection requirements for each work year. (Navy LRMP Manual, 17).

The facility inspections result in a verification of existing BMAR requirements, recording new M&R requirements, and recording deficiencies that are expected to require M&R, along with a recommended accomplishment year. Then cost estimates are prepared to correct the deficiencies. The cost estimates are accomplished in a variety of ways: "Any good quality cost estimating system whether computerized or not may be used with the LRMP system" (Navy LRMP Manual, 69).

An Annual Inspection Summary (AIS) is a fiscal year end summary that includes a detailed deficiency listing, cost summary, and summary of the condition of the facilities. Not only are the deficiencies and costs to repair the deficiencies detailed, but also the mission impact. The AIS is the primary tool in developing the Navy M&R budget; "The budget requests for M&R dollars are developed almost exclusively from the information submitted on the AIS" (Navy LRMP Manual, 14).

Evaluation of Navy LRMP.

Criterion 1: Model represents those salient characteristics that impact facility maintenance requirements. The Navy LRMP methodology directly considers facility condition through the comprehensive facility inspection program. LRMP indirectly considers replacement cost, age, size, facility type, type of construction, and location in the cost estimation for correction of deficiencies. Climate is not considered.

Criterion 2: Model characterizes how maintenance funding requirements vary over time, according to life cycles of facilities and facility systems. The Navy LRMP considers life-cycles of facilities in an indirect manner. The scope of LRMP is over a period of five years into the future, despite using the term "long range". Life-cycles are

considered when determining when a facility, system, or equipment item will require M&R, based on profession judgement of the inspectors.

Criterion 3: Model considers maintenance deferral penalty costs. The Navy LRMP has no mechanism for considering maintenance deferral penalty costs.

Criterion 4: Model uses input data that is currently available to the USAF. The Navy LRMP consists of extensive inspections and condition assessments that are much more intensive than currently accomplished by the USAF. Gathering and maintaining required data to utilize the LRMP methodology would require extensive effort and expense.

Scoring for U.S. Navy LRMP

Replacement Cost	Age	Size	Facility Type	Climate	Construction	Location	Condition	Life-Cycle	Maintenance Deferral Penalty	Data Avail
2	2	2	2	1	2	2	3	2	1	2

Summary of Investigation of Methodologies and Models. The investigation of methodologies and models resulted in nineteen different model that have been proposed and/or are being used to predict facility maintenance and repair funding requirements. The eighteen methodologies are not a complete, exhaustive list of all methodologies; the availability of information, especially with respect to commercial products, limited the number of methodologies that were investigated and evaluated. Revisiting the four general classes or categories of methodologies proposed in Chapter Two would be useful at this point in the analysis. Figure 3 includes the eighteen methodologies that were

investigated, and illustrates the categories, which they fall under. Note that the methodologies often do not fall neatly into one category; instead they are hybrids of two or more categories.

Figure 3. A Taxonomy of Facility M&R Funding Requirements Approaches

Category: Methodology	Replacement Value	Formula Based	Life-Cycle	Condition Assessment
Percentage of Current Present Value				
Percentage of Replacement Value				
Kraft Model				
USCG Methodology				
Dergis-Sherman Formula				
Preventing Deferred Maintenance				
Facilities Renewal Model				
Air Force FIM & PRV Methodology				
SF-based Model				
Incremental Budget				
MRPM-area, age, use Model				
Army ISR				
UNIFORMAT				
MRPM Component Model				
Stanford Model				
BUILDER				
AME				
Navy, LRMP				

There is a wide variety approaches being used to determine facility M&R requirements. The table suggests that the methodologies that were investigated demonstrate a balance between the methodology categories. If a decision-maker is especially interested in methodologies that incorporate one approach, or a combination of approaches, then this taxonomy is a useful tool.

Analysis of Dominance

Once the methodologies have been investigated and scored against the four criteria, evaluation and comparison of the methodologies is possible. The first step in the evaluation and comparison process is an analysis of dominance. The results of the analysis of dominance will answer research questions two and three. An Excel spreadsheet is used to analyze the scores for dominance. Table 3 provides the summary of the scores, sorted by salient characteristic score first, then data availability, life-cycle, and finally maintenance deferral penalty cost.

Table 3. Methodology/Model Scores

Model	SC Sum	Life-Cycle	Maint. Deferral Penalty	Data
Incremental Budget	8	1	1	6
SF-based	10	1	1	6
% of CPV	12	1	1	4
USCG	12	1	1	6
Dergis-Sherman	13	2	1	5
% of PRV	13	1	1	6
Kraft	15	1	1	5
USAF PRV-FIM	15	2	1	6
Navy Long Range Maintenance	16	2	1	2
Preventing Deferred Maintenance	16	4	1	3
Facilities Renewal	18	2	1	3
MRPM-Area, Age, Use	18	2	1	5
Stanford	19	4	1	3
Army ISR	19	2	1	4
MRPM-Facility Component	20	5	1	1
AME	21	4	1	2
UNIFORMAT	21	5	1	3
BUILDER	23	5	3	3

The first issue is to determine if any one methodology is dominant. An evaluation of the criteria scores for each model, reveal that no single model scores higher than all the other methodologies in at least one criterion, with scores that are equal to or higher than

all the other methodologies in the remaining criteria. Therefore, the existing USAF PRV-FIM methodology is not clearly superior, nor is any other methodology clearly superior.

The next step is to determine which methodologies are non-dominated. The method followed in this analysis is to examine each methodology, and determine if it is dominated by at least one other model. If a methodology is dominated, it will be excluded from further analysis. The methodologies that are dominated by at least one other methodology are shaded gray in Table 3. The dominated methodologies, and the methodologies that dominate them, are listed in Table 4.

Table 4. Dominated Methodologies

Dominated Model	**Model is Dominated by:**
Incremental Budget	SF-based, USCG, % of PRV, and USAF PRV-FIM
SF-based	USCG, % of PRV and USAF PRV-FIM
% of CPV	USCG, Dergis-Sherman, % of PRV, and USAF PRV-FIM, Kraft, MRPM-Area-Age-Use, and Army ISR
USCG	% of PRV and USAF PRV-FIM
Dergis-Sherman	MRPM-Area-Age-Use and USAF PRV-FIM
% of PRV	USAF PRV-FIM
Kraft	MRPM-Area-Age-Use and USAF PRV-FIM
Navy Long Range Maintenance	Preventing Deferred Maintenance, Stanford
Preventing Deferred Maintenance	Stanford
Facilities Renewal	MRPM-Area-Age-Use, Stanford, Army ISR, UNIFORMAT, and BUILDER
Stanford	UNIFORMAT and BUILDER
MRPM-Facility Component	UNIFORMAT and BUILDER
AME	BUILDER
UNIFORMAT	BUILDER

The result of the dominance analysis is that four methodologies are non-dominated. These methodologies are:

1. USAF PRV-FIM
2. MRPM Area-Age-Use
3. U.S. Army ISR
4. BUILDER

Even though the dominance analysis was accomplished with the limitation of no available information from a decision-maker, the number of alternatives was reduced significantly.

Lexicographic Method Analysis

The next step in the analysis is to apply the lexicographic method to the non-dominated alternatives. A series of lexicographic orderings will be accomplished, exploring the different orders of preference among the four criteria.

The process of lexicographically ordering the methodologies is accomplished using an Excel spreadsheet. Using the scores summarized in Table 3, the Excel sort function is used to order the four non-dominated methodologies. The sorting is done in descending order, first by the most important criterion, then by the second most important, then by the third most important, and finally by the least important.

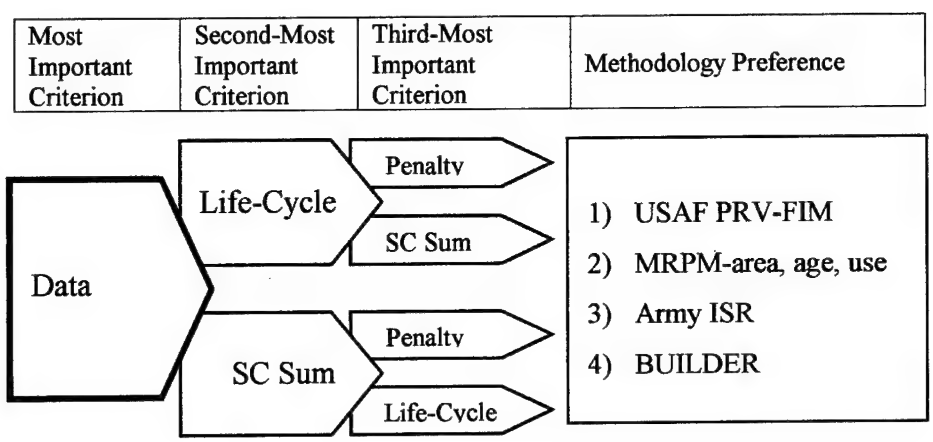
The analysis will be accomplished in four phases, each considering a single criterion as being most important, and then exploring the different combinations of second, third and least (fourth) most important criterion within each case. The analysis is described below, and the results are summarized in Figures 4 through 7.

Data Requirement Criterion. This case assumes that a decision-maker considers the data requirement criterion to be the most important criterion. The first combination to be lexicographically ordered is data requirement (Data); sum of salient characteristics (SC Sum); Life-Cycle; and maintenance deferral penalty cost (Penalty). Data requirement is the most important criterion and penalty is the least important. The result of the lexicographical sort is:

	Most Important	→	→	Least Important
Model	Data	SC Sum	Life-Cycle	Penalty
USAF FIM	6	15	2	1
MRPM-area, age, use	5	18	2	1
Army ISR	4	19	2	1
BUILDER	3	23	5	3

Note that selecting Data as the most important criterion locks-in the preference order for all methodologies. Therefore, no further lexicographic order combinations will change the preference order. Figure 5 illustrates the result. When data requirement is considered to be the most important criterion, the USAF PRV-FIM methodology is the preferable alternative. While the USAF PRV-FIM methodology does not score highly in the other three criteria, it is the only non-dominated methodology that requires input data that is available, maintained, and in an immediately useable format by the USAF.

Figure 4. Lexicographic Method Analysis: Data Criterion Most Important.



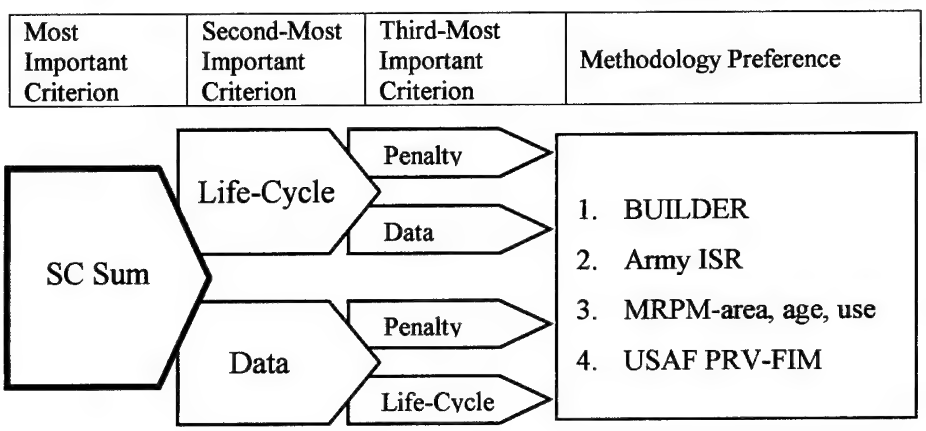
<u>Sum of the Salient Characteristics Criterion</u>. This case assumes that a decision-maker considers the sum of the salient characteristics to be the most important criterion. The first combination to be lexicographically ordered is sum of the salient characteristic (SC Sum); data requirement (Data); life-cycle; and maintenance deferral penalty cost

(Penalty). SC Sum is the most important criterion and Penalty is the least important. The result of the lexicographic sort is:

Model	Most Important → SC Sum	Data	Life-Cycle	Least Important → Penalty
BUILDER	23	3	5	3
Army ISR	19	4	2	1
MRPM-area, age, use	18	5	2	1
USAF FIM	15	6	2	1

Note that selecting SC Sum as the most important criterion locks-in the preference order for all methodologies. Therefore, no further lexicographic order combinations will change the preference order. Figure 5 illustrates the result.

Figure 5. Lexicographic Method Analysis: SC Sum Criterion Most Important



Given that a decision-maker chooses salient characteristics sum as the most important criterion, then BUILDER is the preferable alternative and the USAF PRV-FIM methodology drops to the least preferred of the six non-dominated methodologies.

Life-Cycle Criterion. This case assumes that a decision-maker considers the life-cycle criterion to be the most important criterion. The first combination to be lexicographically ordered is life-cycle; data requirement (Data); sum of salient

characteristics (SC Sum); and maintenance deferral penalty cost (Penalty). Life-cycle is the most important criterion and Penalty is the least important. The result of the lexicographic sort is:

	Most Important ⟶			Least Important
Model	Life-Cycle	Data	SC Sum	Penalty
BUILDER	5	3	23	3
USAF FIM	2	6	15	1
MRPM-area, age, use	2	5	18	1
Army ISR	2	4	19	1

When life-cycle is considered the most important criterion, BUILDER is ranked first; however, USAF FIM, MRPM-area, age, use, and Army ISR have equal life-cycle scores. The data criterion is the next most important criterion, and the data criterion scores are different for the bottom five methodologies, resulting in the preference ranking as shown above. Note that the bottom five methodologies all have the same penalty criterion score; therefore, the penalty criterion has no impact on the preference order when life-cycle is considered the most important.

The only other combination that will change the preference order is Life-cycle, SC Sum, Data and then Penalty. The result of the lexicographic sort is:

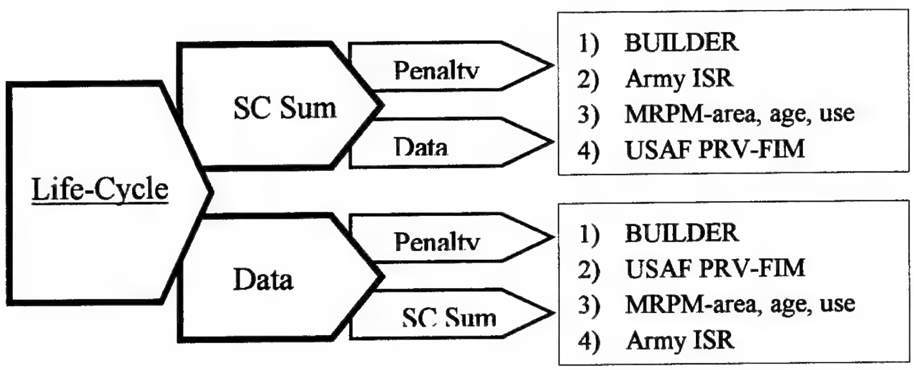
	Most Important ⟶			Least Important
Model	Life-Cycle	SC Sum	Data	Penalty
BUILDER	5	23	3	3
Army ISR	2	19	4	1
MRPM-area, age, use	2	18	5	1
USAF FIM	2	15	6	1

Note that when SC Sum is considered the second most important criterion, the preference order between the Army ISR, MRPM-area, age, use, and USAF PRV-FIM methodologies changes from the case when data was second most important.

Given that a decision-maker selects life-cycle as the most important criterion, then two different methodology preference rankings are possible. Figure 6 illustrates the two different rankings, given the choice of salient characteristic sum or data as the second-most important criterion.

Figure 6. Lexicographic Method Analysis: Life-Cycle Criterion Most Important

Most Important Criterion	Second-Most Important Criterion	Third-Most Important Criterion	Methodology Preference



Penalty Criterion. This case assumes that a decision-maker considers the maintenance deferral penalty cost criterion to be the most important criterion. In this case, the second, third and least important criterion selection has a larger impact on the preference order. This is a result of all the methodologies, except for BUILDER, having equal penalty scores. A more exhaustive analysis of the combinations of the ordering of criterion importance is required.

The first combination to be lexicographically ordered is maintenance deferral penalty cost (Penalty); sum of salient characteristics (SC Sum); data requirement (Data); and life-cycle. Penalty is the most important criterion and life-cycle is the least important. The result of the lexicographic sort is:

	Most Important →			Least Important
Model	Penalty	SC Sum	Data	Life-Cycle
BUILDER	3	23	3	5
Army ISR	1	19	4	2
MRPM-area, age, use	1	18	5	2
USAF FIM	1	15	6	2

The second combination to be lexicographically ordered is penalty cost (Penalty); life-cycle; data requirement (Data); and sum of salient characteristics (SC Sum). Penalty is the most important criterion and SC Sum is the least important. The result of the lexicographical sort is:

	Most Important			Least Important
Model	Penalty	Life-Cycle	Data	SC Sum
BUILDER	3	5	3	23
USAF FIM	1	2	6	15
MRPM-area, age, use	1	2	5	18
Army ISR	1	2	4	19

The third combination to be lexicographically ordered is penalty cost (Penalty); life-cycle; sum of salient characteristics (SC Sum); and data requirement (Data). Penalty is the most important criterion and data is the least important. The result of the lexicographical sort is:

	Most Important →			Least Important
Model	Penalty	Life-Cycle	SC Sum	Data
BUILDER	3	5	23	3
Army ISR	1	2	19	4
MRPM-area, age, use	1	2	18	5
USAF FIM	1	2	15	6

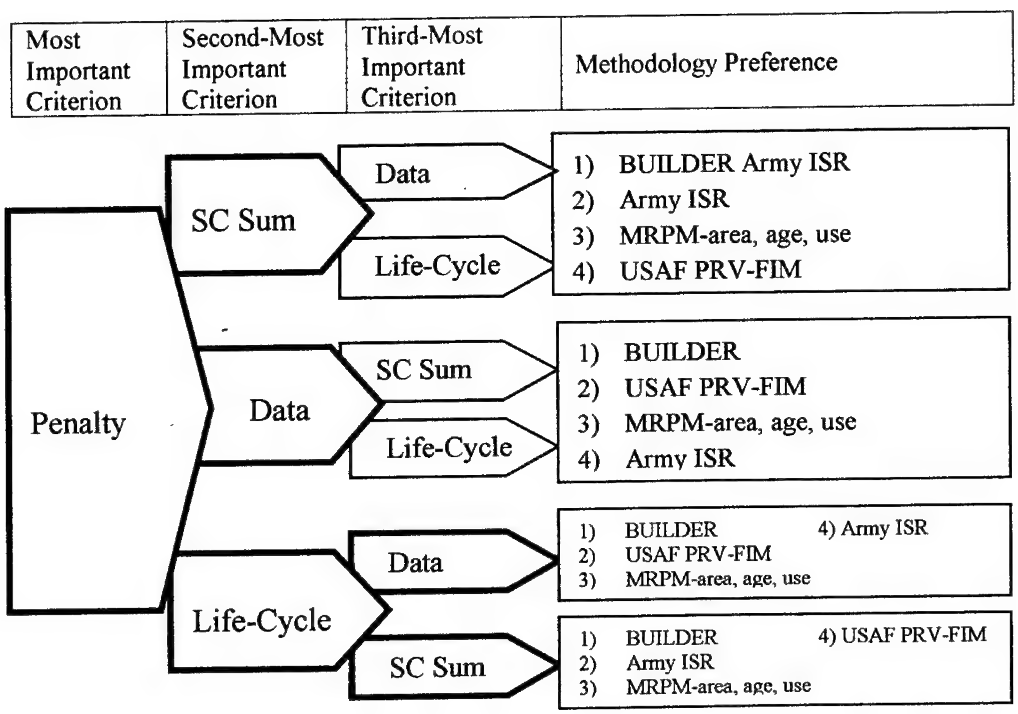
The last combination to be lexicographically ordered is penalty cost (Penalty); data requirement (Data); sum of salient characteristics (SC Sum); and life-cycle. Penalty is

the most important criterion and life-cycle is the least important. The result of the lexicographical sort is:

	Most Important →			Least Important
Model	Penalty	Data	SC Sum	Life-Cycle
BUILDER	3	3	23	5
USAF FIM	1	6	15	2
MRPM-area, age, use	1	5	18	2
Army ISR	1	4	19	2

Given that a decision-maker selects maintenance deferral penalty cost as the most important criterion, then four different methodology preference rankings are possible. Figure 7 illustrates the four different rankings that result from the different combinations of level of importance between criteria.

Figure 7. Lexicographic Method Analysis: Penalty Cost Criterion Most Important



Summary of Lexicographical Analysis. The results from the lexicographical analysis partially answer research question four. This question asked, of the methodologies that are non-dominated, over what ranges of preferences between criteria, are certain methodologies preferred over others? In this case, it is assumed that a decision-maker is able to specify which criteria are most important, but not exactly how much more a criterion is important than another. The lexicographical ordering analysis suggest than the USAF-PRV methodology is the preferred methodology only if using input data that is currently available to the USAF is the most important consideration. Otherwise, BUILDER is the preferred methodology.

In order to determine over what ranges of preferences, rather than what preference orders, between criteria are certain methodologies preferred over others, analysis using cardinal information on the criterion weighting must be accomplished.

TOPSIS Analysis

If the criteria are considered compensatory, and cardinal information is available concerning the weighting of the criteria, then the TOPSIS technique can be applied. The TOPSIS analysis determines the distance of each alternative from both the ideal solution and the negative-ideal solution. The assumption is the best alternative has both the shortest distance from the ideal, and the longest distance from the negative ideal. The distance is determined using the Lp metric as discussed in Chapter Three. The TOPSIS requires cardinal information on the criteria weighting. Because this analysis is not conducted using information from a specific decision-maker, a range of possible weights is considered, and the results of the TOPSIS analysis examined across that range of

criteria weights. The TOPSIS analysis is accomplished using an Excel spreadsheet. The calculations for different weights are easily accomplished once a spreadsheet is constructed; different values for the weights are simply entered into the appropriate cells. The calculations are shown below for the case where the weights are equal: salient characteristic sum = 0.25; life-cycle = 0.25; maintenance deferral penalty = 0.25; and data requirements = 0.25.

The algorithm begins with setting up the decision matrix. The decision matrix contains the four non-dominated methodologies (alternatives) along the rows, and the four criteria (attributes) along the columns. The average SC Score is sum of the salient characteristic criterion scores divided by eight (the number of characteristics). The assumptions behind using the average SC Score were discussed in Chapter Three. The data within the matrix are the criterion scores for each alternative:

Model	Average SC Score	Life-Cycle	Penalty	Data
BUILDER	2.875	5	3	3
USAF PRV-FIM	1.875	2	1	6
MRPM-area, age, use	2.25	2	1	5
Army ISR	2.375	2	1	4

The first step is to construct the normalized decision matrix. The four criteria have different scales, and creating a normalized decision matrix is necessary for comparison between the criteria. Normalizing is accomplished by dividing each criterion score by the norm of the total criterion vector. Using Excel, the norm of each criterion is calculated as the square root of the sum of the squares of each criterion score within the column. For example, the norm of the life-cycle criterion is $[5^2 + 2^2 + 2^2 + 2^2]^{1/2}$.

The norms are:

	Average SC Score	Life-Cycle	Penalty	Data
Sum of Squares	22.48	37	12	86
Normalizing factor	4.74	6.08	3.46	9.27

The normalized decision matrix is created by dividing each score by the criterion's norm.

The normalized decision matrix:

Model	Normalized Average SC Score	Normalized Life-Cycle	Normalized Penalty	Normalized Data
BUILDER	0.6063	0.8220	0.8660	0.3235
USAF PRV-FIM	0.3954	0.3288	0.2887	0.6470
MRPM-area,age,use	0.4745	0.3288	0.2887	0.5392
Army ISR	0.5009	0.3288	0.2887	0.4313

Step two is to enter the criterion weights. In this calculation, the weights are:

	Average SC Score	Life-Cycle	Penalty	Data
Criterion Weight	0.25	0.25	0.25	0.25

The weighted, normalized decision matrix is now calculated by multiplying each normalized score by the criterion's weight. The normalized, weighted, decision matrix:

Model	Weighted, Normalized Average SC Score	Weighted, Normalized Life-Cycle	Weighted, Normalized Penalty	Weighted, Normalized Data
BUILDER	0.1516	0.2055	0.2165	0.0809
USAF PRV-FIM	0.0989	0.0822	0.0722	0.1617
MRPM-area,age,use	0.1186	0.0822	0.0722	0.1348
Army ISR	0.1252	0.0822	0.0722	0.1078

Step three is to determine ideal and negative ideal solutions. For every criterion considered in the analysis, the greater the score, the more beneficial; therefore, the ideal solution is an "imaginary" alternative comprised of the maximum of the four weighted, normalized criterion scores. The negative-ideal solution is an "imaginary" alternative consisting of the minimum of the four weighted, normalized criterion scores. Given the normalized, weighted, decision matrix above, the ideal and negative-ideal solutions are:

	Weighted, Normalized Average SC Score	Weighted, Normalized Life-Cycle	Weighted, Normalized Penalty	Weighted, Normalized Data
Maximum score	0.1516	0.2055	0.2165	0.1617
Minimum score	0.0989	0.0822	0.0722	0.0809

Step four is to calculate the separation measure. The separation measure is determined using the Lp metric, when p=1, 2, and ∞. The separation measure and preference ranking will be calculated below for each of the three cases. When p=1, the separation measure is commonly referred to as the Manhattan or rectilinear distance. The separation measure for each alternative is the sum of the absolute value of the difference between weighted, normalized criteria scores and the ideal criteria scores. The separation from the ideal (p=1):

Model	Average SC Score	Life-Cycle	Penalty	Data	Positive Separation Measure
BUILDER	0.0000	0.0000	0.0000	-0.0809	0.0809
USAF PRV-FIM	-0.0527	-0.1233	-0.1443	0.0000	0.3204
MRPM-area,age,use	-0.0330	-0.1233	-0.1443	-0.0270	0.3275
Army ISR	-0.0264	-0.1233	-0.1443	-0.0539	0.3479

The separation from the negative ideal (p=1):

Model	Average SC Score	Life-Cycle	Penalty	Data	Negative Separation Measure
BUILDER	0.05272	0.12330	0.14434	0.00000	0.32036
USAF PRV-FIM	0.00000	0.00000	0.00000	0.08087	0.08087
MRPM-area,age,use	0.01977	0.00000	0.00000	0.05392	0.07369
Army ISR	0.02636	0.00000	0.00000	0.02696	0.05332

Where p=2, the separation measure is commonly referred to as the Euclidean distance. The separation measure for each alternative is calculated as the square root, of the sum of the squares, of the difference between the weighted, normalized scores and the ideal alternative scores. The separation from the ideal (p=2):

Model	Average SC Score	Life-Cycle	Penalty	Data	Sum of Squares	Positive Separation Measure
BUILDER	0.0000	0.0000	0.0000	-0.0809	0.0065	0.0809
USAF PRV-FIM	-0.0527	-0.1233	-0.1443	0.0000	0.0388	0.1970
MRPM-area,age,use	-0.0330	-0.1233	-0.1443	-0.0270	0.0378	0.1945
Army ISR	-0.0264	-0.1233	-0.1443	-0.0539	0.0396	0.1991

The separation from the negative ideal (p=2):

Model	Average SC Score	Life-Cycle	Penalty	Data	Sum of Squares	Negative Separation Measure
BUILDER	0.05272	0.12330	0.14434	0.00000	0.03882	0.19702
USAF PRV-FIM	0.00000	0.00000	0.00000	0.08087	0.00654	0.08087
MRPM-area,age,use	0.01977	0.00000	0.00000	0.05392	0.00330	0.05743
Army ISR	0.02636	0.00000	0.00000	0.02696	0.00142	0.03771

Where p=∞, the separation measure is referred to as the Chebechev distance. The positive separation measure for each alternative is defined as the smallest of the four individual criteria separations from the positive ideal. The criterion that minimizes the maximum separation from the ideal is the only criterion considered when determining the separation. The separation from the positive ideal (p=∞):

Model	Average SC Score	Life-Cycle	Penalty	Data	Positive Separation Measure
BUILDER	0.0000	0.0000	0.0000	0.0809	0.0000
USAF PRV-FIM	0.0527	0.1233	0.1443	0.0000	0.0000
MRPM-area,age,use	0.0330	0.1233	0.1443	0.0270	0.0270
Army ISR	0.0264	0.1233	0.1443	0.0539	0.0264

The negative separation measure for each alternative is defined as the largest of the four individual criteria separations from the positive ideal. The criterion that maximizes the minimum separation from the negative ideal is the only criterion considered when determining the separation. The separation from the negative ideal (p=∞):

Model	Average SC Score	Life-Cycle	Penalty	Data	Negative Separation Measure
BUILDER	0.05272	0.12330	0.14434	0.00000	0.14434
USAF PRV-FIM	0.00000	0.00000	0.00000	0.08087	0.08087
MRPM-area,age,use	0.01977	0.00000	0.00000	0.05392	0.05392
Army ISR	0.02636	0.00000	0.00000	0.02696	0.02696

Note that there are three different sets of separation measures for any given set of weights. The use of three Lp metrics result in different relative closeness to ideal solution results and consequently, different preference rankings among the four non-dominated methodologies.

Step five is to calculate the relative closeness to the ideal solution. The ranking of alternatives is based upon the alternative being both close to the ideal, and far from the negative ideal. The measure of relative closeness is the distance from the negative-ideal divided by the sum of the distance from the ideal and the distance from the negative-ideal. The relative closeness to the ideal solution for each alternative is:

Model	Relative Closeness to Ideal Solution (p=1)	Relative Closeness to Ideal Solution (p=2)	Relative Closeness to Ideal Solution (p=∞)
BUILDER	0.7984	0.7090	1.0000
USAF PRV-FIM	0.2016	0.2910	1.0000
MRPM-area,age,use	0.1837	0.2279	0.6667
Army ISR	0.1329	0.1592	0.5056

Step six is to rank the preference order. A value of one is the highest relative closeness to the ideal solution. The final step is simply to sort the relative closeness values in descending order. In each of the three cases they are already in descending order, BUILDER is the preferred methodology, then USAF PRV-FIM, MRPM-area, age, use, and Army ISR.

To reiterate, the preference ranking above is for an equal criterion weighting of 0.25. In order to answer research question four, "Of the methodologies that are non-

dominated, over what ranges of preferences among criteria are certain methodologies preferred over others?" the relative closeness values for each alternative are easily calculated for various weights by using the Excel spreadsheet.

The general trend of the scores for the methodologies investigated, is that methodologies with higher scores for salient characteristic, life-cycle, and penalty criteria, generally have greater data requirements, and consequently do not score as high on the data criterion. Therefore, it would be informative to determine the relative closeness to the ideal solution for a range of data criterion weights from zero to one. For the purposes of the analysis, it will be assumed that the weighting for the other three criteria are equal to (1- data weight)/3. Given the three Lp metrics, Figures 8 through 10 show the relative closeness to the ideal of the four non-dominated methodologies as the weight of the data criterion is varied from zero to one.

Figure 8. TOPSIS Analysis: p=1, Equal Criteria Weighting

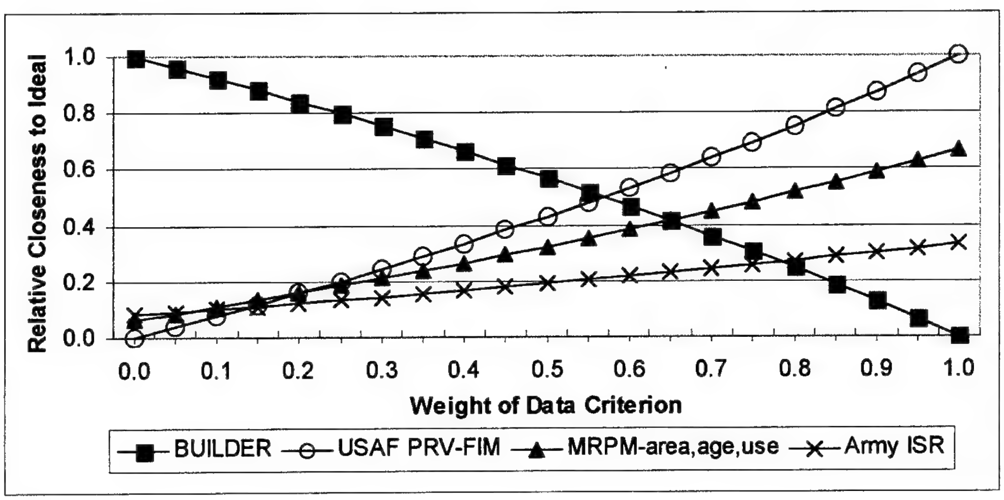


Figure 9. TOPSIS Analysis: p=2, Equal Criteria Weighting

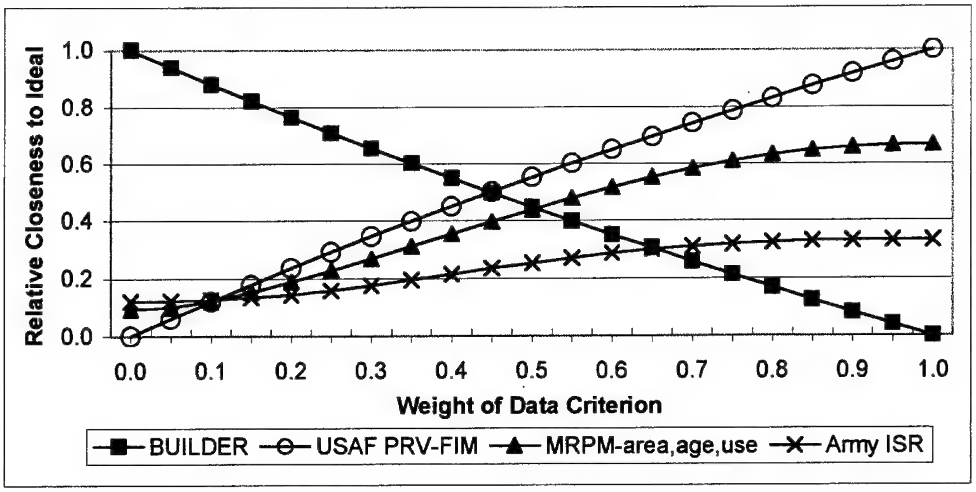
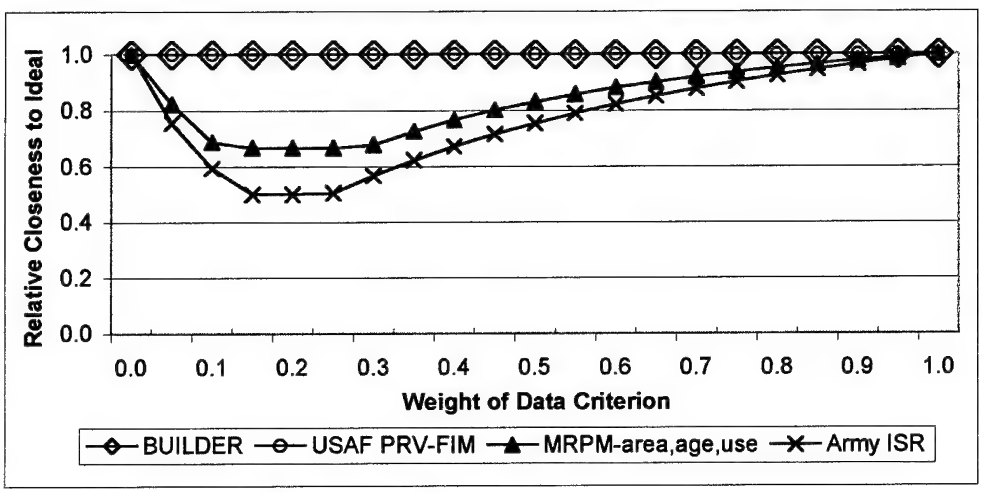


Figure 10. TOPSIS Analysis: p=∞, Equal Criteria Weighting



When the salient characteristic, life-cycle, and maintenance deferral penalty criteria weights are held equal, while varying the data criterion weight from zero to 100%, the results of the TOPSIS analysis suggests the following:

1. When p=1 or p=2, and the data criterion is given a weight of 100%, the preferable alternative is the USAF PRV-FIM. The MRPM-area, age, use methodology also scores well.

2. When p=1 or p=2, and the data criterion is given no weight (0%), the preferable alternative is BUILDER. The other three methodologies score significantly lower that BUILDER and therefore, appear to be inferior alternatives.

3. When using the p=1 metric, USAF PRV-FIM and BUILDER rank the same when the data criterion weighting is approximately 55%. When the data criterion weight is less than 55%, then BUILDER is preferred. When the data criterion weight is greater than 55%, then the USAF PRV-FIM is preferred.

4. When using the p=2 metric, USAF PRV-FIM and BUILDER rank the same when the data criterion weighting is approximately 45%. When the data criterion weight is less than 45%, then BUILDER is preferred. When the data criterion weight is greater than 45%, then the USAF PRV-FIM is preferred.

5. When using the $p=\infty$ metric, USAF PRV-FIM and BUILDER rank the same, regardless of the weight of the data criterion. In this case, the use of a totally non-compensatory metric results in USAF PRV-FIM receiving a perfect score of 1.0 because it has the highest score in the data criterion. BUILDER receives a perfect score because it has the highest scores in the salient characteristic, life-cycle, and maintenance deferral penalty cost criteria. The totally non-compensatory metric considers only the criterion that is closest to the ideal, and ignores the other criteria deviations.

The above analysis assumes that the weights of the salient characteristic, life-cycle, and maintenance deferral penalty criteria remain equal. Another assumption might be that life-cycle and maintenance deferral penalty cost are not as important as the salient characteristic and data requirement criteria. This assumption reflects a short-term viewpoint, because the life-cycle and maintenance deferral penalty cost criterion are both integral to accurately modeling facility M&R funding requirements over the long-term. In the DoD, and most federal agencies, the budget planning process is based upon a five-year window. Five years is short-term in light of building life expectancies that range from fifty to one hundred years.

Further analysis which modifies the weighting of the life-cycle and maintenance deferral penalty cost criterion is useful, in order to gain some additional perspective on determining over what ranges of preferences between criteria, are certain methodologies

preferred over others. Using the TOPSIS analysis, three cases will be examined and the results compared. Within each case, the three Lp metrics will be considered.

<u>Case 1</u>. The original analysis, where weights of the salient characteristic, life-cycle, and maintenance deferral penalty criteria remain equal to each other, and vary according to the weight for the data requirement criterion.

<u>Case 2</u>. The weights for life-cycle and maintenance deferral penalty cost criteria are held constant at 10% each. The salient characteristic and data requirement criteria are then varied.

<u>Case 3</u>. The life-cycle and maintenance deferral penalty cost criteria are give no (0%) weight, and the salient characteristic and data requirement criteria are then varied.

The analysis of these cases is accomplished by entering the appropriate weights into the Excel spreadsheet, and recording the results, which are shown in Figures 11 through 15. The figures represent the results for case 2 and case 3, examining each Lp metric. Case 1 results were shown in Figures 8 through 10. Note that in case 2, the range for the of the data criterion weight does not exceed 0.80. This is because the life-cycle and maintenance deferral penalty cost criteria are fixed at 0.10 each, leaving 0.80 to be divided among the remaining two criteria.

Figure 11. TOPSIS Analysis: Case 2; p=1 metric

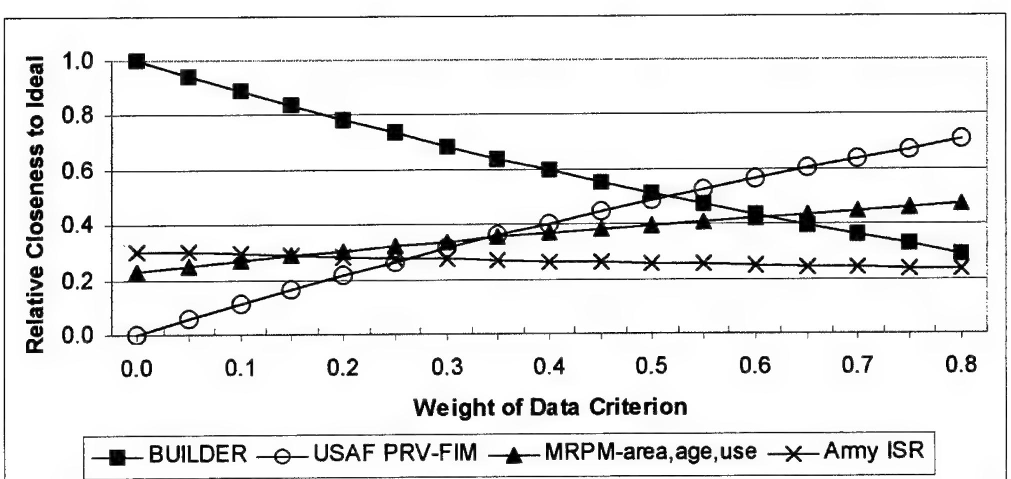


Figure 12. TOPSIS Analysis: Case 2; p=2 metric

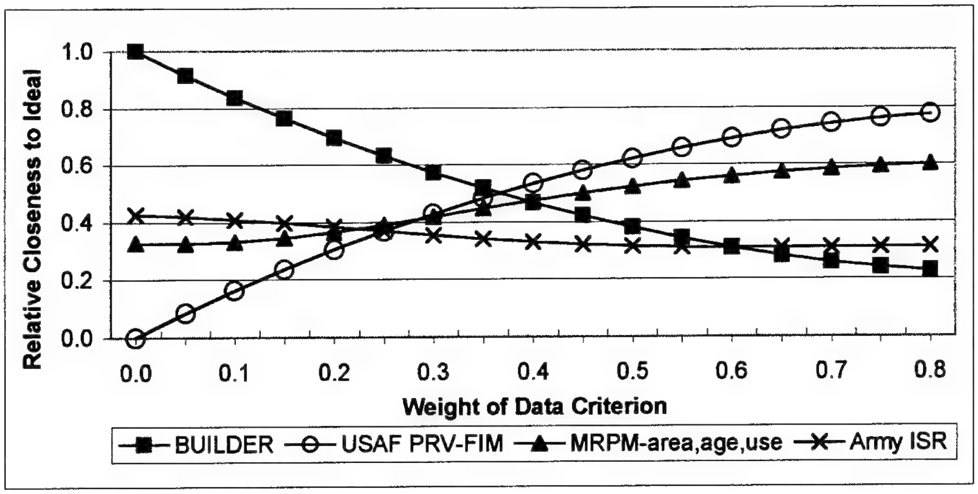


Figure 13. TOPSIS Analysis: Case 2; p=∞ metric

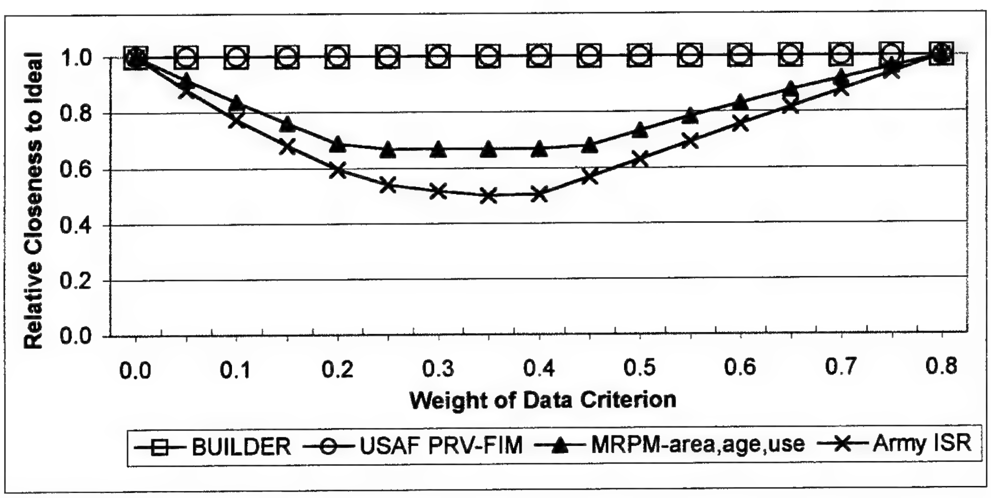


Figure 14. TOPSIS Analysis: Case 3; p=1 metric

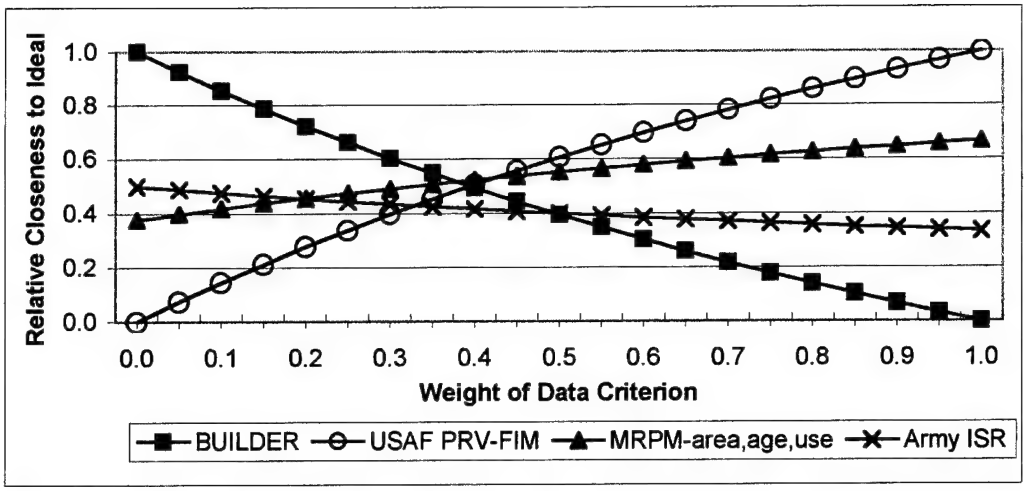
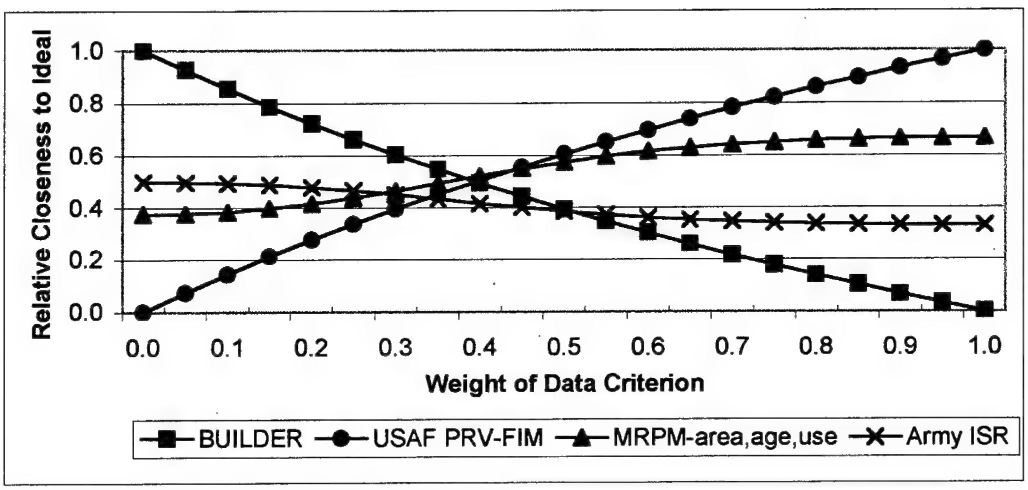


Figure 15. TOPSIS Analysis: Case 3; p=2 metric



Note that a figure was not created for case 3 when p=∞ because all four methodologies have a relative closeness to ideal of 1.0 across the entire range of data criterion weights.

The results of the TOPSIS analysis of the three cases suggest that reducing the weighting for the life-cycle and maintenance deferral penalty cost criteria does not have a large impact on determining over what ranges of preferences between criteria, are certain

methodologies preferred over others. When the life-cycle and maintenance deferral penalty cost criteria weights are reduced, the required weight of the data criterion at which the USAF becomes preferable to BUILDER drops from approximately 55% (case 1) to 50% (case 2) and 40% (case 3) when p=1. When p=2, the required weight of the data criterion at which the USAF becomes preferable to BUILDER drops from approximately 45% (case 1) to 37% (case 2) and 40% (case 3). This is a reasonable outcome, because the strength of the BUILDER methodology is its scores in the life-cycle and maintenance deferral penalty criterion. The strength of BUILDER's scores in the salient characteristic criterion still makes BUILDER preferable to the USAF PRV-FIM methodology until the data requirement criterion weighting approaches the range of 37% to 55%. The results when p=∞ do not provide much differentiation between the methodologies. This is because a high score for any one criterion will result in a high relative closeness to the ideal, regardless of the scores for the other criterion. In this case, the lexicographic method appears to be a more sensible because it allows the decision maker to decide the criterion which will dominate the preference order.

Chapter Summary

This chapter presented the results of the research and analysis accomplished towards the resolution of the four research questions posed in chapter 1. Eighteen methodologies for determining appropriate facility M&R funding requirements were investigated. The methodologies were discovered through a combination of literature search and interviews with personnel who developed and/or utilize the models. According to the MCDM processes established in Chapter Three, the methodologies were

evaluated against the four criteria established as primary factors in determining facility M&R requirements.

An analysis of dominance was accomplished and it was determined that no single methodology dominated the others; however, only six of the eighteen methodologies were non-dominated. An exhaustive series of lexicographical orderings was accomplished on the six non-dominated methodologies. The general result of the lexicographical analysis was that, because of its superior consideration of the salient characteristics, life-cycle, and maintenance deferral penalty cost criteria, BUILDER is the preferable choice, unless data requirement is the most important criterion. Where data requirement is considered more important than any other criteria, the current USAF PRV-FIM methodology is preferable for USAF use.

A TOPSIS analysis was performed with the six non-dominated methodologies. The TOPSIS analysis includes the use of weights for the criteria, rather than a simple ordering of preferences between criterion as is used with lexicographic ordering. The TOPSIS analysis suggested that BUILDER is the preferable methodology until the weight for the data requirement criterion exceeds a range of 30% to 40%.

V. Conclusions and Recommendations

Chapter Overview

This chapter reviews the four research questions, and provides a short summary of the findings for each question. The next part of this chapter presents the logical conclusions resulting from the research. This chapter discusses some limitations of the research effort. Finally, recommendations for further research are presented.

Summary of the Findings

Research Question 1. What categories or classes of methodologies have been developed to predict facility maintenance and repair funding requirements?

The process of literature review and personal interviews resulted in the consideration of eighteen models and methodologies. It was determined through the review of the literature, that there are four general approaches to determining funding requirements for facility M&R. An analysis of the eighteen models resulted in a taxonomy of facility M&R funding requirement approaches (Figure 3). The eighteen models and methodologies represented a balanced mixture of the four approaches, and in many cases the models and methodologies were hybrids of two or more of the approaches.

Research Question 2. Is the existing USAF PRV-FIM methodology clearly superior in its appropriate application to USAF requirements? If not, are any of the methodologies identified through this research clearly superior?

The process of determining if any of the methodologies is clearly superior in its appropriate application to USAF requirements consisted of evaluating and scoring the methodologies against the criterion which were established through a consensus of expert opinion in the literature. The MCDM technique of dominance was applied once the methodologies were scored. The result was the USAF PRV-FIM methodology is not clearly superior, nor is any other methodology.

Research Question 3. If no single methodology is clearly superior, which methodologies are non-dominated in their appropriate application to USAF requirements?

The analysis for dominance revealed that fourteen of the eighteen methodologies were dominated by at least one other methodology. Dominance suggests that if a methodology were dominated by other methodologies, there would be no reasonable instance when a logical decision-maker would prefer the dominated methodology to a dominant methodology. Therefore, the fourteen dominated methodologies were eliminated from further consideration. The four methodologies that received further consideration are referred to as the set of non-dominated methodologies; they were:

1. USAF PRV-FIM
2. MRPM Area-Age-Use
3. U.S. Army ISR
4. BUILDER

Research Question 4. Of the methodologies that are non-dominated, over what ranges of preferences between criteria, are certain methodologies preferred over others?

Given the four non-dominated methodologies, lexicographic ordering and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) were utilized to

explore the range of preferences between criteria, where certain methodologies might be preferred over others.

The process of lexicographic ordering consists of a decision-maker determining which criterion is most important to the selection of the "best" methodology. The results of an exhaustive series of the possible combinations of lexicographic ordering, suggests that the current USAF PRV-FIM methodology is only preferable when the most important consideration is the data requirement criterion. The data requirement criterion measures the extent that the methodology uses data that is currently available, maintained, and in an immediately useable format to the USAF. If data requirement is not the single most important consideration, then according to the analysis in this research, BUILDER is the preferable methodology. The technique of lexicographic ordering does not incorporate consideration of weighting amongst the four criteria; therefore, TOPSIS was used as an additional step in answering this research question.

The result of the TOPSIS analysis was, if the data requirement criterion receives 100 percent of the weight, then the current USAF PRV-FIM methodology is the preferable methodology. This agrees with the results from the lexicographic analysis. The TOPSIS technique allowed for analysis over a range of weighting between the criterion. As a result of examining several different combinations of weighting, the TOPSIS analysis suggests that the USAF PRV-FIM methodology is the preferable methodology when the weight of the data criterion ranges from 100 percent down to 55 to 40 percent of the total weight of all four criteria. When the weight of the data criterion is less than 55 to 40 percent, then BUILDER is the preferable methodology.

Conclusions

The problem of deciding which methodology to adopt in determining funding requirements for maintaining USAF facilities is a very difficult decision. The fact that a wide variety of methodologies have been proposed and used, suggests a lack of consensus as to which approach is most useful and appropriate. Prior to this thesis effort, no objective comparison of the existing methodologies had been conducted to decide which methodology is best suited for determining appropriate levels of investment in facility maintenance and repair. The intent of this research effort was to accomplish such an objective comparison.

It is interesting to note that the four non-dominated methodologies identified in this effort represent the entire spectrum of approaches described in the literature, as show in Figure 16.

Figure 16. Taxonomy of Non-Dominated Methodologies

Category: Methodology	Replacement Value	Formula Based	Life-Cycle	Condition Assessment
Air Force FIM & PRV Methodology				
MRPM-area, age, use Model				
Army ISR				
BUILDER				

This result tends to support the idea that each approach has its merits. The replacement value and formula based approaches have the benefit of low data requirements. The life-cycle and condition assessment approaches tend to more accurately model a facility inventories M&R requirements; however, they have much more intensive data requirements.

Within the limitations of the process followed during this research, it can reasonably be concluded that the current USAF PRV-FIM methodology may not be the methodology best suited for USAF facility maintenance and repair level of investment determination. This research suggests that the U.S. Army Corps of Engineers BUILDER model may best serve the USAF in justifying to Congress and public its facility maintenance and repair level of investment determination. This conclusion holds true unless it is decided that the effort and expense of collecting and maintaining the additional data required by BUILDER is not reasonable.

If requiring additional data to be collected and maintained is not acceptable, then the current USAF PRV-FIM methodology, despite its shortcomings, appears to be the best alternative among available models and methodologies. This conclusion is not surprising; it is the classic conflict between weighing the cost against the benefits. In this case, it is the cost of gathering additional data against the benefit of using a methodology which effectively models the maintenance and repair requirements of a facility inventory.

The fact that the DoD is the steward of over $500 billion of the nation's assets in facilities and infrastructure represents an obligation to identify the true requirements for facility and infrastructure maintenance and repair. Over the time period from FY 1987 to FY 1996, DoD funding for maintenance and repair fell approximately 38 percent while reductions in SF of space owned and managed by the DoD fell only 10 percent (GAO/NSIAD, 1997: 4). The need to establish an accepted methodology for determining appropriate maintenance and repair requirements is important now more than ever.

Limitations of the Research Effort

The analysis accomplished in the process of this research focused on four criteria. These criteria were selected as the primary factors appropriate to the specific issue of forecasting and defending USAF facility maintenance and repair funding requirements. While the use of the four criteria is reasonable, it is not accurate to say that they encompass the entirety of the issue. Through the process of the entire research effort, several other potentially important factors became evident.

One factor is the level of resolution at which the methodologies are capable of operating. Some methodologies are only applicable at the macro (plant) level, while others apply at the facility or facility system level. Some methodologies operate with a short-term (less than 5 years) predictive horizon, while others are capable of determining requirements over the lifetime of a facility. Finally, some methodologies are capable of consideration of a constrained budget and consequently incorporate trade-offs and priorities into the budget determination. Figure 17 expands upon the taxonomy of facility maintenance and repair approaches which was presented in Chapter Four. It illustrates which of the eighteen methodologies investigated in this research consider these additional factors. While the methodologies were not evaluated against these factors, they may be important to consider in other situations and are therefore presented for reference.

Figure 17. Additional Factors

Methodology	Approach (Table 2)				Level of Resolution			Predictive Horizon		Constrained Budget
	Replacement Value	Formula Based	Life-Cycle	Condition Assessment	System	Facility	Plant	Short-term	Long-term	
% of CPV	■						■	■		
% of PRV	■						■	■		
Kraft	■						■	■		
USCG	■	■					■	■		
Dergis-Sherman	■	■	■				■	■	■	
Prev. Deferred Maint.	■		■				■	■	■	■
Facilities Renewal	■		■				■	■	■	
USAF FIM-PRV	■			■			■	■		■
SF-based		■					■	■		
Incremental Budget		■					■	■		
MRPM-area, age, use		■	■				■	■	■	
Army ISR		■		■		■	■	■		
UNIFORMAT			■		■	■	■		■	
MRPM Component			■		■	■		■	■	
Stanford			■				■		■	
BUILDER			■	■	■	■	■	■	■	■
AME			■	■			■		■	■
Navy LRMP				■	■	■	■	■		■

As in the selection of criteria, the analysis focused on USAF requirements. A reader outside the USAF must consider that the scoring of the methodologies against the data criterion in particular holds true only for USAF requirements. One benefit of the relatively simple MCDM techniques that were used, and the use of Excel to accomplish the calculations, is the analysis can be re-accomplished using different scoring for any of the criteria.

Areas for Further Research

The primary area for further research lies in exploring the trade-off between the cost of data collection and the benefits of utilizing methodologies that require the additional data. The lack of data in the area of facility maintenance and repair budgeting is clear; however, there has been little effort towards determining how much data is required to make accurate predictions of facility maintenance and repair funding requirements.

Another area worthy of further investigation is the motivation behind the use of a different methodology by every DoD agency. It is reasonable to assume that because all DoD agencies are funded from the same source, and the inventory of facilities is reasonably similar, that a common methodology could be used. Is it reasonable that different methodologies are used? How does that affect the process by which DoD agencies compete against each other for the limited maintenance and repair resources?

This thesis effort investigated existing models and methodologies. It would be useful to conduct an optimization exercise to determine what the "ideal" model for USAF facility M&R budgeting needs would consist of.

Appendix: UNIFORMAT Methodology Tables

Table A-1. UNIFORMAT Building Component Structure

Level 2	Level 3
01 Foundations	011 Standard Foundations
	012 Special Foundation Conditions
02 Substructure	021 Slab on Grade
	022 Basement Excavation
	023 Basement Walls
03 Superstructure	031 Floor Construction
	032 Roof Construction
	033 Stair Construction
04 Exterior Closure	041 Exterior Walls
	042 Exterior Doors and Windows
05 Roofing	
06 Interior Construction	061 Partitions
	062 Interior Finishes
	063 Specialties
07 Conveying Systems	
08 Mechanical	081 Plumbing
	082 HVAC
	083 Fire Protection
	084 Special Mechanical Systems
09 Electrical	091 Service and Distribution
	092 Lighting and Power
	093 Special Electrical Systems
10 General Conditions and Profit	
11 Equipment	111 Fixed and Moveable Equipment
	112 Furnishings
	113 Special Construction
12 Site Work	121 Site Preparation
	122 Site Improvements
	123 Site Utilities
	124 Off-Site Work

Secondary Source: (Melvin, 1992: 50)

Original Source: Dell'Isola, A., Value Engineering in the Construction Industry. New York: Van Nostrand Reinhold, 1975, 76-78.

Table A-2. Relationship between UNIFORMAT and MASTERFORMAT

Level 2 Design UNIFORMAT		01 General Requirements	02 Site-work	03 Concrete	04 Masonry	05 Metals	06 Wood – Plastic	07 Thermal-Moisture Protection	08 Doors and Windows	09 Finishes	10 Specialties	11 Equipment	12 Furnishings	13 Special Construction	14 Conveying Systems	15 Mechanical	16 Electrical
	U UCI																
01 Foundations	011 Standard Foundations		■	■	■												
	012 Spec. Foundation Cond.		■			■											
02 Substructure	021 Slab on Grade		■	■				■									
	022 Basement Excavation		■														
	023 Basement Walls			■	■			■									
03 Superstructure	031 Floor Construction			■		■	■										
	032 Roof Construction			■		■	■										
	033 Stair Construction			■		■	■										
04 Exterior Closure	041 Exterior Walls			■	■	■	■	■		■	■						
	042 Ext. Doors and Windows								■								
05 Roofing							■	■									
06 Int. Construction	061 Partitions				■		■		■		■						
	062 Interior Partitions			■			■			■							
	063 Specialties					■	■				■						
07 Conveying System															■		
08 Mechanical	081 Plumbing															■	
	082 H.V.A.C															■	
	083 Fire Protection															■	
	084 Spec. Mech. System															■	
09 Electrical	091 Service and Distribution																■
	092 Lighting & Power																■
	093 Spec. Electrical System																■
10 Gen. Cond. OH&P		■															
11 Equipment	111 Fixed & Moveable Equip.											■					
	112 Furnishings												■				
	113 Special Construction													■			
12 Sitework	121 Site Preparation		■														
	122 Site Improvements		■	■	■	■					■					■	
	123 Site Utilities		■													■	■
	124 Off-Site Work		■														

Secondary Source: (Melvin, 1992: 51)

Original Source: Dell'Isola, A., Value Engineering in the Construction Industry. New York: Van Nostrand Reinhold, 1975, 74.

Table A-3. Mean Life Cycle of Building Components

Building Component	Average Life
Foundations, floors, structural walls, Roof structures, stairs	75 years
Roofing (including coverings, insulation, and specialties	20 years
Interior walls and doors, windows	50 years
Wall and floor finishes, paint, wall Coverings, and carpeting	7 years
Ceiling finishes	20 years
Elevators	40 years
Fire protection equipment	50 years
HVAC	20 years
Plumbing (water and sewer)	40 years
Electrical (including wiring, switches Receptacles, and fixtures)	30 years
Special equipment (including appliances, (bookcases, and cabinetry)	25 years

Secondary Source: (Melvin, 1992: 50)

Original Source: Peter Lufkin, Estimation of Building Maintenance and Life-Cycle Renewal Costs" (unpublished paper), p. 8.

Bibliography

Applied Management Engineering. http://www.idirect.net/ame_ns2.htm#ame03, 1997

Applied Management Engineering and Sean C. Rush. Managing the Facilities Portfolio. Washington DC: National Association of College and University Business Officers, 1991.

Barco, A. L. "Budgeting for Facility Repair and Maintenance," Journal of Management in Engineering: July/August, 1994, 28-34.

Building Research Board. Committing to the Cost of Ownership: Maintenance and Repair of Public Buildings, APWA Special Report #60. Chicago: APWA, 1991.

Christian, John and Amar Pandeya. "Cost Predictions of Facilities." Journal of Management in Engineering: January/February 1997, 52-61.

The Civil Engineering Research Foundation. "Levels of Investment Study: Facilities and Infrastructure Maintenance and Repair." Report to Headquarters, U.S. Air Force, Civil Engineering Programs, Washington D.C. August 1996.

Clemen, Robert T. Making Hard Decisions: An Introduction to Decision Analysis. Belmont, CA: Duxbury Press, 1996.

Federal Facilities Council Standing Committee on Operations and Maintenance. Budgeting for Facilities Maintenance and Repair Activities, Report #131. Washington D.C.: National Academy Press, 1996.

Hjelmstad, K. D. and others. The Building Materials Durability Model (BMDM): A Comparative Model for Service Life Factors Affecting Materials Selection. USACERL Technical Report 96/24, US Army Corps of Engineers Construction Research Laboratories, January 1996 (ADA303481).

Hutson, Robert, E. and Frederick M. Biedenweg. "Before the Roof Caves In: A Predictive Model for Physical Plant Renewal," in Critical Issues in Facilities Management. Edited by Association of Physical Plant Administrators of Universities and Colleges. Alexandria: APPA, 1989.

Hwang, Ching-Lai and Kwangsun Yoon. Multi Attribute Decision Making Methods and Applications, A State-of-the-Art Survey. New York: Springer-Verlag, 1981.

Kaiser, Harvey H. "Preventing Deferred Maintenance," AIPE Facilities: September/October, 1995, 24-31.

Keck, Harold W. Jr. An Investigation of the Army's Construction Engineering Research Laboratory's Models for Applicability in Determining AF Building Maintenance Supply Budget Requirements. MS thesis, AFIT/GEE/CEM/92S-11. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB, OH, September 1992

Melvin, Eric. Plan. Predict. Prevent. How to Reinvest in Public Buildings. Chicago: American Public Works Association, 1992.

Monterecy, Orestes P. A Formula Budgeting Model and Framework for Controlling Physical Plant Deferred Maintenance: An Empirical Analysis of Public Schools in Rhode Island. PhD dissertation. University of Connecticut, Storrs, Connecticut, 1985.

Murphy, Rich, LCDR, United States Coast Guard Office of Civil Engineering, Washington D.C. Telephone Interview. 19 September 1997.

Neely, Edgar S. and others. Maintenance Resource Prediction in the Facility Life-Cycle Process. U.S. Army Construction Engineering Research Laboratory: Technical Report P-91/10 (AD-A236424), May 1991.

Neely, Edgar S. and Robert Neathammer. "Life-Cycle Maintenance Costs by Facility Use," Journal of Construction Engineering and Management, 117:2: 310-320 (June 1991).

Ozernoy, Vladimir M. "Choosing the 'Best' Multiple Criteria Decision-Making Method," INFOR 30:2: 159-171 (May 1992).

Phillips, Cushing Jr. "Facilities Renewal: The Formula Approach," in Critical Issues in Facilities Management. Edited by Association of Physical Plant Administrators of Universities and Colleges. Alexandria: APPA, 1989.

Sherman, Douglas R. and William A. Dergis. "A Funding Model for Building Renewal", Planning for Higher Education, 9:3: 21-25 (Spring 1981).

U.S. Air Force, Air Force Facility Investment Metric: Executive Overview, 1 August 1997.

U.S. Army Cost and Economic Analysis Center (USACEAC), Installation Status Report Cost Factor Methodology, 1997.

U.S. Department of Defense. Renewing the Built Environment: Real Property Maintenance Activities. Department of Defense Report to Congress, 16 March 1989.

U.S. General Accounting Office. Defense Infrastructure: Demolition of Unneeded Buildings Can Help Avoid Operating Costs. GAO/NSIAD-97-125. Washington D.C., 13 May 1997.

U.S. General Accounting Office. Deferred Maintenance: Reporting Requirements and Identified Issues. GAO/AIMD-97-103R. Washington D.C., 23 May 1997.

U.S. Navy, Long Range Maintenance Planning Program Manual, Version 3.1

Uzarski, D. R. and L. W. Burley. "Assessing Building Condition through the Use of Condition Indices." Proceedings of American Society of Civil Engineers Specialty Conference Infrastructure Condition Assessment: Art, Science, Practice: (365-374) August 1997.

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13. ABSTRACT *(Maximum 200 words)*

Eighteen methodologies for forecasting facility maintenance and repair funding requirements were investigated and analyzed to determine which methodology is best suited for use by the United States Air Force (USAF). The literature review identified four primary factors, or criteria, that determine facility maintenance and repair funding requirements. The methodologies were scored against the four criteria with respect to their appropriate application to USAF requirements. An analysis of dominance was accomplished; the results suggested that no one methodology was clearly superior. Fourteen of the methodologies were dominated, and consequently eliminated from further analysis. Four methodologies were non-dominated: the U.S. Army Construction Engineering Research Laboratories (USACERL) BUILDER; USACERL Maintenance Resource Prediction Model; U.S. Army Installation Status Report; and the USAF Plant Replacement Value-Facility Investment Metric (PRV-FIM). Further analysis was accomplished using the multi-criteria decision-making techniques of lexicographic analysis and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The results suggested the USAF PRV-FIM methodology is only preferable when the most important consideration is limiting the amount of data that must be collected and maintained. Otherwise, the USACERL BUILDER methodology may best serve the USAF in justifying to Congress and the public, its facility maintenance and repair level of investment determination.

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